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LED lamps - photometric and electrical performance

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Hehkulamppujen poistuttua markkinoilta LED-lamppujen valikoima on lisääntynyt voimakkaasti viime vuosina. Nämä korvikelamput ovat helposti kuluttajan saatavilla, toisin kuin kalliimmat LED-valaisimet. Tästä syystä diplomityössä keskitytään nimenomaan lamppujen ominaisuuksiin.
Tässä työssä luotiin katsaus ledilamppuihin liittyvään lainsäädäntöön, aikaisempiin mittauksiin ja tutkimuksiin, joihin pohjautuen suoritettiin mittauksia. Lamput valittiin mittauksiin ensisijaisesti saatavuuden, eri ostohintojen ja 60 W hehkulampun korvaavuuden perusteella.
Lamppujen suorituskykyä testattiin mittaamalla valovirta ja -tehokkuus, tehonkulutus ja sähkön laatu sekä väriarvot ja valon laatu. Lamppujen käyttöikää arvioitiin polttoikäkokeella, jossa lamppuja vanhennettiin 6000 tuntia. Vanhennusdataa ekstrapoloitiin L70-arvon ja nimellisen käyttöiän selvittämiseksi TM-21 metodilla. Myös lamppujen valonjako mitattiin goniometrilla valaistustuloksen arvioimiseksi.
Tulosten perusteella suurin osa lampuista täytti niille asetetut vaatimukset. Ledilamput olivat selvästi muita lampputeknologioita parempia valontuoton ja -tehokkuuden kannalta, tarjoten jopa 70-100 lm/W valotehokkuuden. Lamppujen eliniän ennusteet ylittivät useimmissa tapauksissa 30000 tuntia. Seurauksena arvioidut osto- ja käyttökustannukset tulivat ledilampulle muita teknologioita edullisemmaksi.
Valonjakomittauksista kävi kuitenkin ilmi, että lamppujen valonjako poikkesi huomattavasti hehkulampusta. Seurauksena saattaisi ilmetä ongelmia tiettyjen valaisimien kanssa, mutta tämä ei käy kuluttajille ilmi lamppujen myyntipakkauksista. Tämä on selkeä puute Euroopan markkinoilla ja saattaa vaikeuttaa kuluttajan ostopäätöksiä.

Avainsanat: LED, LED-lamppu, Ledilamppu, LED-valaistus, ledien elinkaari, ledien valovirran alenema, ledien valonjako, L70

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ABSTRACT OF THE MASTER'S THESIS

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Due to withdrawal of the incandescent lamp, recent years have witnessed a myriad of new LED lamps on the market. These LED retrofit lamps, unlike more expensive LED luminaires, are easily available to the consumer and thus the focus of attention in this thesis.

The thesis reviews related legislation, previous benchmarks and studies to establish and justify a framework for lamp measurements. Several LED lamp models were selected for testing, based on criteria of availability, full price range and claimed equivalency to 60 W incandescent lamp.

The lamps were tested for photometric and electrical performance such as luminous flux and -efficacy, power consumption and -quality and colour quality. Furthermore, lamps were subjected to 6000 h ageing test to discover their long-term performance, survivability and stability. The ageing data was extrapolated for L70-value and lifetime estimation using TM-21 methodology. Finally, the lamps were measured in goniometer to measure angular luminous intensity distribution and test their suitability of the lamps in different luminaires.

The results revealed majority of the tested lamps conforming to most of the regulations and requirements. LED lamp performance exceeded existing technologies by a fair margin and boasted efficacies of 70-100 lm/W. The longevity predictions indicated lifetimes exceeding 30000 hours. Thus, combined purchasing and operating costs of LED lamps were estimated to be lower than that of other lamp technologies.

However, lamp luminous intensity distributions differed greatly from incandescent lamp, indicating potential problems with some luminaires. This difference was not obvious to the consumer from lamp packages, which may complicate decision-making of the consumer and exacerbate adoption of LED lamps.

Keywords: LED, LED lamp, LED Luminaire, LED performance, LED longevity, LED lumen depreciation, L70, LED luminous intensity distribution

Preface

Twelve months ago I started the preliminary research into my thesis. What was expected to be relatively quick process turned out as a vast odyssey. This paper is a report on and testament to the work conducted. Personally, having just lost a job and broken up with a long-time girlfriend had left its mark. Yet, even beyond depression and grief, a small, bright spark of intrigue remained, compelling to face the challenges ahead.

However, nothing could prepare me for the sheer magnitude of the task ahead. Long hours within the black-painted walls of the lighting laboratory, the seemingly endless racks of light-bulbs demandingly waiting for measurement and the hollow atmosphere of a night at the department that could drive a man to madness. The progress was slow, full of setbacks and dead-ends as well as seemingly endless hours of work on writing and correcting spelling. A daunting task that might have discouraged me, had I seen it beforehand... But then again, that is the essence of research and life; to boldly embark on a journey to the unknown no matter how intimidating the way ahead appears. I must thus properly offer my sincerest thanks and gratitude to everyone involved in that very journey.

I wish to thank my Supervisor Prof. Liisa Halonen and Instructor D.Sc (Tech.) Eino Tetri for remarkable guidance and insight as well as patience with sometimes glacial pace of progress.

Warm thanks to the whole of the staff of the Lighting Unit of Aalto University for their support and help with literature and information searching of academia.

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Sincere thanks to M.Sc colleagues Mikko Maksimainen and Esko Aalto for related and non-related conversations and special thanks to Esko for bringing new, interesting LED lamps to my attention.

Warmest thanks to my parents and relatives, near and far, for their invaluable support during the process as well as for hosting (and especially feeding) me during weekend visits.

Last but not least, thanks for my friends for their empathy and emotional support during difficult, stressful times. With them, every day felt like an adventure with challenges, failures and triumphs. That adventure has merely just begun...

Carpe diem!

Otaniemi, 6.5.2014

Niko Rolamo

Contents

Symbols and abbreviations

Symbols

$\mathbf{\Phi}$	Luminous flux [lm]
$\theta_{\frac{1}{2}}$	Half-intensity angle of luminous intensity distribution
λ	Wavelength of electromagnetic radiation [nm]
K	Degrees Kelvin in correlated colour temperature
P	Electrical Power
PF	Power Factor
I	Electrical current
U	Voltage
UV	Ultraviolet light
$\mathbf{R_a}$	General colour rendering index

Abbreviations

LED	Light-emitting Diode
CFL	Compact Fluorescent Lamp
R&D	Research and Development
E27	27 mm Edison screw socket
EU	The European Union
EC	The European Commission
DC	Direct Current
AC	Alternating Current
IES	Illuminating Engineering society
IEC	International Electrotechnical Commission
CCT	Correlated Colour Temperature
CRI	Colour Rendering Index
CIE	International Commission on Illumination
SSL	Solid-State Lighting
EPA	Environment Protection Agency of United States
DOE	Department of Energy, United States of America
EMC	Electromagnetic Compatibility
EMI	Electromagnetic interference
RAPEX	Rapid Exchange of Information System of the European Commission
SPD	Spectral Power Distribution
SMPS	Switch-mode Power Supply
TRIAC	Triode for Alternating Current - a solid-state AC switching component

1 Introduction

As the traditional incandescent lamp fades into obscurity, new technologies are quickly filling the void it left. This development is driven by ever stricter efficiency requirements imposed by National and Federal governments in Europe as well as in USA [1]. The replacements for Edison's iconic light-bulb, which are often referred to as retrofit lamps or replacement lamps, exist in many varieties, shapes and sizes. The two most prominent technologies are compact fluorescent lamp (CFL) and light-emitting diode (LED). However, due to very rapid development of the latter, sales of the more mature CFL technology are in decline. The lighting industry has realised the potential of LEDs as a light source and are investing heavily in their research and development (R&D) [2]. It can thus be seen that LED will be the dominant light source for the years to come. It could be argued that LED components themselves would be better suited for specifically designed LED luminaires due to their unique technical characteristics [63]. However, the Edison screw socket (E-socket), especially the 27mm variant E27, has proven hard to replace due to its overwhelmingly widespread use in luminaires throughout the World, the European Union and Finland [3]. It is thus feasible to focus on the most easily accessible LED light sources on the market, the retrofit lamps.

The first LED retrofits were introduced roughly a decade ago with very limited power and a myriad of issues regarding lifetime, overheating and light quality. Whilst LEDs themselves had developed incredibly rapidly, LED lamp performance was still lagging behind the CFL in 2010 [4]. LED lamps weren't yet ready to challenge CFL in higher powers such as the very popular 60W incandescent equivalent. Recent years, however, have witnessed a virtual explosion in the variety of new, better LED lamps. Throughout their existence, LED lamps have been marketed with superlatives which have rarely withstood more critical enquiry. The inferior early performance resulted into considerable scepticism and bad prestige from the consumer viewpoint, a reputation that even presently hampers LED lamp acceptance. Therefore, many studies, reviews and benchmarks have attempted to remedy the situation. As the LED technology grew more mature, better products started to appear on the market, a fact obvious from latest test results [5] [6] [7] [8].

However, many of these tests have failed to consider LED lamp lifetime, a figure typically boasted in marketing speech. LED lamps still have purchase prices double or triple that of a contemporary CFL. Thus, to offer savings over CFL, the lifetime of LED lamps needs to exceed that of the CFL by a fair margin. Thus, obtaining a good, reliable lifetime estimate is crucial to accurate evaluation of usage costs and payback period of an LED lamp. This alone is of high importance because it almost single-handedly dictates whether the consumer should purchase LED lamps to replace other technologies [10].

LED lamps have multiple ageing mechanisms, the two most important being complete failure and gradual degradation of light output. Aside from total failure, the rated life of an LED product is most commonly defined as the time its light output has decreased to 70% of initial, also known as the L70-value [9] [10]. Because this time can be very long, typically in excess of 10000 hours or more, direct testing would simply be impractical due to unyieldingly long times to market. Thus, different methods have been proposed for finding an estimate for the L70, based on extrapolation of shorter-term real data. The most common method is a 6000-hour ageing test in room temperature [11] [12]. However, to estimate long-term performance from this data, an extrapolation method is applied. The reliability of such prediction has been tested by some authors in the past [14] [15]. Another method is accelerated ageing test, where the test group is exposed to elevated temperature to physically speed up the ageing process. These tests have been given considerable research effort, but LED lamp and luminaire lifetime estimation is still a rather obscure territory, mostly due to limited availability of recent physical ageing data [15].

The main focus of this thesis is to examine the performance and usability of modern LED retrofit lamps. Whilst LED retrofit lamps are indeed available for many different sockets and applications, the thesis focuses solely on retrofits of non-directional light output, E27-screw socket and 60W incandescent-equivalent light output. This decision was made to limit the labour and consumable costs of the testing. A consideration was also given to follow a tradition of similar lamp tests conducted in the Lighting Unit of Aalto University (previously Helsinki University of Technology) for passed 90 years [4] [16].

Chapter 2 examines central legislation and standards related to LED lamps. This is done in order to establish a framework for testing of the lamps. European regulations are examined in contrast to those of USA to discover the main differences between the two market areas. Furthermore, standards are reviewed for approved methodologies for testing LED lamps in addition to established practices of the Lighting Unit of Aalto University. The chapter also searches and reviews usable methods for testing LED lamp ageing and service life.

Chapter 3 begins with a background on the retrofit lamp technology. The aim is to establish basic knowledge of LED lamp structure and mechanisms of creating white light in contrast to previous technologies. The thesis also uses the structural overview to recognise possible points of failure for service life estimation and failure analysis.

Chapter 4 reviews LED lamp benchmarks from recent years in order to find trends in LED development. The chapter also reviews recent test results of LED retrofit lamps in order to identify interesting lamp models for further investigation and for overall perspective on LED lamp development. The chapter then moves on to articles and research papers concerning LED ageing testing to discover suitable methodologies for LED lamp lifetime estimation. Chapter 4 finishes with a market survey and presents the lamps selected for testing.

Chapter 5 describes the testing methodology used to measure photometric and electrical properties of the lamps being tested. It also introduces the selected lifetime extrapolation method, the TM-21 [17] and justifies its use in the data analysis.

Chapter 6 presents the results of the conducted tests described in previous chapter. Initially, the chapter tests conformance to general performance requirements, discussed in chapter 2. The chapter analyses and extrapolates the lumen maintenance data from the ageing test and estimates the L70-value for the lamps. The chapter then continues to estimate usage costs of the lamps and compares them to traditional solutions. Finally, the chapter overviews luminous intensity distribution results from the goniophotometric tests and discusses possible problems related to non-standard distributions.

The final chapter 7 concludes the thesis, summarising the findings and reflecting back on the research work done. The chapter also discusses future prospects on possible further energy savings and forecast for the technology.

2 LED-related regulations and standards

This thesis aimed to overview what is exactly required of lamps on the European market in order to better understand the studied lamps. The thesis uses the work of a predecessor as basis, but expands and updates the available information to present day [4]. Furthermore, this overview also establishes a framework for testing the selected lamps later in the thesis. Chapter 2 is divided into two distinct sections. The first section, 'Legal regulations for LED lamps', reviews legislation that affects lighting products and specifically lamps on the consumer market. It answers the questions 'why' and 'what', and is more consumer-centered in nature. The second section, 'Standards', overviews technical standards and requirements that establish a set of guidelines to design and testing engineers. The section answers the question 'how' and is more technically oriented.

2.1 Legal regulations for LED lamps

2.1.1 The European Union Ecodesign directive

In 2009, the European Union Commission recognised the need for reducing energy consumption union-wide. This was mostly done in order to reduce carbon emissions to limits set by the famous 20-20-20 policy, as a part of the climate and energy package in 2009 [18]. The EuP directive (2005/32/EU) was to be replaced by an updated one, aimed to create a framework for ecological design of energy-consuming products. In relation to lighting and lamps, the commission had arranged an impact assessment which studied different options from complete inaction to self-regulation by member states. The report also compared different alternative light sources to incandescent lamp in order to assess the feasibility of the proposed directive. It has to be noted, however, that LED technology in 2009 wasn't yet mature enough to directly compete with CFL or other alternatives and as such received only a passing notion. In conclusion, the report stated the planned EcoDesign directive (2009/125/EU) was likely to be the most efficient option [19].

The EcoDesign directive emerged as a result of the enquiries and hearings. As a directive, it doesn't impose direct regulations or legally binding pacts, but rather a framework to establish product-specific regulations. Overall, the directive aims to both direct manufacturers towards more ecological designs in products and to inform consumers about energy efficiency. As with framework directives in general, the directive itself doesn't accomplish this, but merely sets ground for actual legislation to take place. Following sections will overview regulatory actions taken under the EcoDesign directive.

2.1.2 The European Commission Regulation (EC) 244/2009

Concerning non-directional household lamps, a regulation (EC) N:o 244/2009 was published in 18.3.2009. As a regulation, it became legally binding in all member states. The central aim and purpose of the regulation was to increase market penetration of energy efficient lamps. Non-directional lamps, in this case, refer to lamps whose half-intensity light distribution angle, $\theta_{1/2}$, exceeds 120 degrees. Lamps with luminous flux less than 60 lm and special purpose lamps were also excluded. For the lamps that were included under the regulation, there were three important themes: efficacy, functionality and consumer information.

The regulation was designed such that the efficacy requirements get progressively stricter in six stages. It has to be noted that whilst the regulation does not prohibit incandescent lamps directly, the efficacy of a given incandescent lamp is insufficient to pass the requirements set by regulation 244/2009. The first stage, entered in force first of September 2009, practically removed all diffused (frosted) incandescent lamps from the market as the least efficient light source. At the time of writing, the plan has entered stage 5 from the beginning of September 2013. Table 1 presents the timing and effects of each phase. The regulation defines energy efficacy of lamps by energy classes from A to G, where A is the most efficient. Section 2.1.3 presents directive and method for calculating lamp energy class.

Table 1: Effects of each efficacy requirement stage for non-diffused lamps [20].

Stage	Date	Applies to lamps	Allowed energy classes							Effect in practice
1	1.9.2009	>950lm	A	B	C	D	E	F	G	>100W Incandescent lamps withdrawn
		Others	A	B	C	D	E	F	G	
2	1.9.2010	>725lm	A	B	C	D	E	F	G	>75W Incandescent lamps withdrawn
		Others	A	B	C	D	E	F	G	
3	1.9.2011	>450lm	A	B	C	D	E	F	G	>60W Incandescent lamps withdrawn
		Others	A	B	C	D	E	F	G	
4	1.9.2012	>60lm	A	B	C	D	E	F	G	15W, 25W and 40W incandescent lamps withdrawn
5	1.9.2013	Stricter operational requirements	A	B	C	D	E	F	G	See table 2
6	1.9.2016	Halogen lamps with special sockets G9, R7	A	B	C	D	E	F	G	Low voltage (12V) and xenon-filled halogen lamps withdrawn
		Others	A	B	C	D	E	F	G	

It can be seen from the table that by the year 2016, all other incandescent light sources except B-class halogen lamps should be withdrawn from the market. It can also be seen how the gradual ban of incandescent lamps progressed in the European economic zone.

Another important topic of EC 244/2009 was operational requirements for lamps. Initial requirements were established in 1.9.2009 as the first phase of the regulation came into effect. These were constricted further in September 2013, mainly affecting older models of CFL. Table 2 presents the requirements in phase 1 and phase 5 respectively

Table 2: Operational requirements by EC244 for CFL and LED.

Operational parameter	Stage 1	Stage 5
Survival factor at 6000 h	≥0.5	≥0.7
Lumen maintenance	2000 h: ≥0.85 (≥0.8 for domed CFL)	2000 h: 0.88 (≥ 0.83 for domed CFL)
Switching operations	≥half of the rated life in hours >10 000, if start time > 0.3 s	≥rated life in hours > 30 000 if start time > 0.3s
Start time	< 2.0s	< 1.5s for powers < 10W < 1.0s for powers ≥ 10W
Warm-up time	< 60s (to 60% of nominal flux) < 120s for amalgam CFL*	<40s (to 60% of nominal flux) < 100s for amalgam CFL*
Premature failure	≤ 2% at 200 h	≤ 2% at 400 h
UVA + UVB	≤ 2.0 mW / klm	
UVC	≤ 0.01 mW / klm	
Power factor	> 0.50 for powers < 25W > 0.90 for powers ≥ 25W	> 0.55 for powers < 25W > 0.90 for powers ≥ 25W
Colour rendering index (Ra)	≥80	

*CFL technologies described in chapter 3.3

The regulation also makes it compulsory to inform consumer about the product. The product information must be made freely accessible on the packaging and open website. These requirements came into effect along with phase 2 for all lamps conforming to phase 4 requirements and onwards. Following information was made compulsory in package labels:

- Luminous flux
- Nominal lifetime in hours
- Number of switching cycles
- Correlated colour temperature
- Warm-up time to 60% of full luminous flux
- A warning if the lamp is not compatible with incandescent lamp dimmers
- Optimal ambient conditions if they differ from nominal (i.e. $T_{\mathrm{amb}} \neq 25°\mathrm{C}$)
- Lamp dimension in millimetres
- If a lamp claims to replace incandescent lamp of certain power, its luminous flux must conform to table 3

Table 3: Required luminous fluxes for standard incandescent lamp powers [1].

Incandescent lamp power [W]	Luminous flux of the replacing lamp [lm]		
	Halogen	CFL	LED and others
15	119	125	136
25	217	229	249
40	410	432	470
60	702	741	806
75	920	970	1055
100	1326	1398	1521
150	2137	2253	2452
200	3009	3172	3452

It should be noticed from the table that LEDs face stricter requirements than other light sources. This was justified in the regulation by the assumed fact that LEDs, as extremely long-lived products, slowly lose their luminous flux over time. Whilst an LED would have higher initial flux, it would cross the required level during its lifetime. LED ageing processes are described in detail by chapter 3.5.

EC 244 also provided a framework for market supervision conducted by national or union-wide conformity and safety agencies and manufacturers alike. According to the regulation, a random sample of at least 20 lamps per model must be tested for conformity. For a model to conform to EcoDesign requirements, the averaged result for any parameter should not vary more than 10% of the set values in operational requirements. The methods of measurement should be generally accepted, reliable and accurate [4]. The parameters to be measured are:

- Mercury content
- Lamp socket dimensions
- Luminous efficacy
- Operating lifetime
- Start time and warm-up time

The regulation did not pass without a rather heated rhetoric and criticism. It also didn't come across without some potential weaknesses. The effects of the regulation initially met fierce resistance, mainly due to lack of affordable and effective retrofit lamps at the time. The CFL was criticised for a multitude of reasons and the LED was still in its infancy. People started stockpiling incandescent lamps while vendors could still sell them, even so much that some supply chains ran out of lamps for some time. The withdrawal of frosted incandescent lamps met especially harsh opposition. The frosted dome lamp provided more diffused light with less glare than its non-frosted counterpart, making it more suitable for many types of luminaire. Even a hint of rebellion was witnessed in form of heat-resistant silicon caps that could be applied on clear incandescent lamps to make them more diffused [21].

By referring to 'household lamps', the regulation excludes lamps made for special purpose. This loophole allowed some vendors to start selling 'heating lamps' and 'rough service lamps' following the regulation. These were basically regular incandescent lamps sold under the pretext of being made and intended for special purpose [22]. However, as estimated in the impact assessment, this has remained rather marginal phenomenon [19].

2.1.3 Household lamp package labels

The European Commission Directive 98/11/EC was put into effect with one central aim: to inform the consumer about energy efficiency of lamps in a concise and consistent way. The directive described an energy label to be used in product packaging as well as a method to calculate the energy class of any given lamp covered by the directive. The original energy label had a scale from A to G with A being the most efficient.

Recently, a new regulation 874/2012 introduced new energy classes A+ and A++ for modern LED lamps that could not have be foreseen in 1998 [23]. This was mainly done to aid the consumer selecting between already energy efficient lamps; otherwise all approved lamps would have resided in group A, making comparison impossible. The energy class of a lamp depends on both its input power and nominal luminous flux. This regulation also updated the method for calculating energy classes. The new method utilises energy efficiency index (EEI), which is used to determine the energy class of a lamp. Table 4 presents EEI limiting values for both directional and non-directional lamps.

Table 4: Energy efficiency classes for lamps [23].

Energy efficiency class	**EEI for non-directional lamps**	**EEI for directional lamps**
A++ (most efficient)	EEI ≤ 0.11	EEI ≤ 0.13
A+	0.11 < EEI ≤ 0.17	0.13 < EEI ≤ 0.18
A	0.17 < EEI ≤ 0.24	0.18 < EEI ≤ 0.40
B	0.24 < EEI ≤ 0.60	0.40 < EEI ≤ 0.95
C	0.60 < EEI ≤ 0.80	0.95 < EEI ≤ 1.20
D	0.80 < EEI ≤ 0.95	1.20 < EEI ≤ 1.75
E (least efficient)	EEI > 0.95	EEI > 1.75

The document also provides a formula for calculating actual EEI, based on lamp luminous flux and actual power. EEI for lamps with luminous flux less than 1300 lm is defined by formula 1:

$$EII = P_{cor} \cdot (0.88\sqrt{\Phi_{use}} + 0.049 \cdot \Phi_{use}), \tag{1}$$

where the P_{cor} is correlated (actual) lamp power Φ_{use} actual luminous flux of the lamp. Determining lamp energy class is possible using this formula and limits from table 4.

In addition to the updated method, the new regulation also presents the new energy label with its shape and colour constraints. A model of the new label is presented in figure 1.

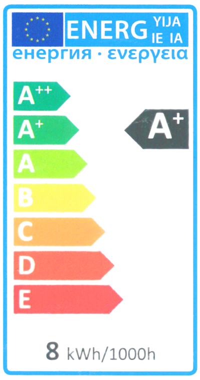

Figure 1: Typical retrofit lamp energy label.

Conspicuously, energy classes from C to E still remain in the energy label whilst they are no longer being sold. It makes little sense to keep these classes in the label as they are redundant and taking up a lot of visual space [24]. It is unknown why the Commission decreed to keep these categories in the label.

2.1.4 The Energy Star

Energy star program and service mark is an international equivalent for the European package markings and performance requirements. Originally created by Environmental Protection Agency (EPA) of USA, it has also been adopted in Canada, Japan, New Zealand, Australia Taiwan and also the European Union, although it is only practically used in USA. The Energy Star mark, somewhat akin to the European CE-mark, is applied to energy-consuming products. It is, if possible, more comprehensive and exhaustive than European requirements and thus has possibly driven the development of LED lamps in USA much further.

Central idea behind the Energy Star marking is to ensure that all products sporting it conform to stringent performance, efficiency and longevity requirements. The consumer can trust that these are high quality products. The Energy Star marking is, unlike the CE-marking of the EU, not a requirement, but its absence can hurt a product's sales and reputation in the eyes of the consumers.

Central requirements of the Energy Star qualification are similar yet stricter than EU performance regulations. Furthermore, additional requirements are in place, especially related to non-standard lamps. Table 5 presents a short summary of differing requirements.

Table 5: Central Energy Star requirements differing from EU regulations [25].

Operational parameter	Energy Star requirement			EC 244/2009 [1]
Correlated colour temperature [12]	Nominal CCT	Target CCT and tolerance	Target Duv and tolerance	No such requirements
	2700 K	2725 ± 145	0.000 ± 0.006	
	3000 K	3045 ± 175	0.000 ± 0.006	
	3500 K	3456 ± 245	0.000 ± 0.006	
	4000 K	3985 ± 275	0.000 ± 0.006	
Colour maintenance [12]	Change of chromaticity less than 0.007 on CIE1976 during 6000hr test period			No such requirements
Lumen maintenance [12]	≥ 70% lumen maintenance at 25000 hours			88% at 2000h (Table 2)
Minimum luminous efficacy [12]	50 lm/W for lamp powers < 10W 55 lm/W for lamp powers ≥ 10W			20.8 lm/W for 806 lm clear non-directional lamp [1]
Colour rendering index (CRI)	Minimum CRI (R_a) of 80. Additionally, $R_9 > 0$			Minimum CRI of 80
Power factor	PF > 0.7 for lamps > 5W			PF > 0.5 for lamps < 25W

A notable feature in Energy Star is minimum luminous efficacy requirement for LED lamps. Whilst the minimum efficacy of 50 or 55 lm/W is rather conservative by modern standards, it was an important milestone in 2011 when the document was published [25]. It almost single-handedly denied inferior products the energy star label and thus persuaded industry to invest in R&D effort for better lamps.

Another interesting element is the clear division between replacement lamps and non-standard lamps. Requirements for replacement lamps luminous intensity distribution are much more strict than with corresponding EU regulation. The energy Star specifies retrofit lamps should have even luminous intensity distribution from 0 ° to 135 ° instead of simply having half intensity at a cone of 60 ° as in regulation 244/2009. The energy star also requires that 5% of total luminous flux must be emitted in the 135 °-180 ° zone [25]. This has undoubtedly driven the development of truly omni-directional LED lamps in the USA in contrast to wide variety of different lamps in the EU.

Lamps that do not conform to the requirements stated above are considered non-standard lamps, which affects the package labelling of the lamp. As discussed later in the thesis, the luminous intensity distribution from a CFL or an LED lamp can be rather different from incandescent lamp. Whether or not a lamp is suitable for a specific application depends largely on the distribution of light. For instance, a decorative floor-lamp might require more omni-directional intensity distribution to create the desired lighting effect. A table spot luminaire or 'desk-lamp' with reflector would undoubtedly benefit from a more directional light source, where less light would be wasted in reflector losses. However, the consumer has no practical way of knowing the luminous intensity distribution or even lamps suitability for specific application unless it is clearly stated in the package. Thus, the Energy Star program has adopted application icons for non-standard lamps. These icons, printed onto lamp packages, give the consumer a rough idea of the applications of the given lamp. Figure 2 presents an example of the application icons.

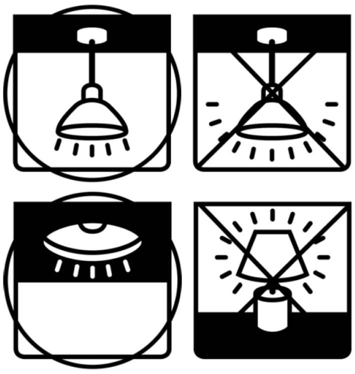

Figure 2: Examples of Energy Star application icons for non-standard lamps. [25]

Similar icons could be useful in EU also, but for reasons obscure, the system has not been adopted in Europe. This thesis will return to the subject in the Conclusion and propose symbols such as these to be used in European markets as well.

2.1.5 ROHS and WEEE

The RoHS and WEEE are environmental directives attempting to both limit the harmfulness of electronic waste and facilitate its recycling and proper handling to reduce environmental impact. The so called RoHS (Restriction of Hazardous Substances) directive (2002/95/EC) aims to limit hazardous materials in electrical and electronic devices in order to reduce impact of the waste products on the ecosystem. The directive covers the use of following substances:

- Lead (Pb)
- Mercury (Hg)
- Cadmiun (Cd)
- Hexavalent chromium
- Polybrominated biphenyls (PBB) and -diphenyls (PBDE)

For lamps, the most relevant ones are mercury and lead. The use of mercury is forbidden with the exception of CFLs containing less than 5mg of mercury.

WEEE (Waste Electrical and Electronic Equipment) directive (2002/96/EC) on the other hand aims to streamline recycling of electronic waste. The directive obligated producers to take part in funding the recycling of their products. In addition, member states were obligated to inform consumers about the potential risks of harmful substances in electrical and electronic waste. The member states were also required to supervise indication of the waste by producers. The studies conducted indicated that merely 27.9% of all lamp waste was recycled [26]. Thus, one of the central aims of WEEE directive was to increase this percentage.

The WEEE directive was eventually recast as a new directive 2012/19/EU with a new, ambitious goal of increasing the degree of recycling up to 85%. It was estimated that the volume of WEEE would increase from present 10 to 12 million tons by 2020, mainly due to shortened lifespan of electronics, and the task of achieving a degree of recycling that high is thus not easy [27].

The new WEEE directive also aims to tackle another problem, which isn't directly affecting Europe: illegal exports of hazardous waste. Many defunct and out-of-date computers, for instance, have been transported to developing countries under guise of 'used equipment'. In practice, most of this material ends up on illegal landfills in Africa and other developing regions, increasing environmental impact and endangering local living conditions [28]. The new directive forces exporters to test and provide documents on the nature of the shipments, especially when running the risk of being waste.

However, certain shortcomings limit the scope and penetration of these directives. As European Union directives, they are limited within EU borders. As it can be seen from the state of industry, most of the potentially waste-producing manufacturing industry resides outside EU region and is thus out of the scope of these directives. Thus, the directives only affect products produced or exported within EU and do not pose any limitations to foreign manufacturing industry in their own waste-handling. It can therefore be seen that while the end product may be environmentally safe, it may not be the case for the industrial processes responsible for its production. Environmental hazards posed by electronics manufacturers have indeed been reported in recent years, mostly occurring, but also not limited to, developing regions of the world.

2.2 Standards

Standards are an important tool in industrial quality control as well as market supervision. Lighting standards are published to harmonise technology, testing and practices throughout the lighting industry. This thesis aims to both examine and apply the reviewed standards to methodology used in testing LED lamps later in the thesis. It has to be noted that most of the European lighting standards are relatively new and rather general in their requirements and testing methodology. Thus, this thesis also reviews equivalent American lighting standards and approved methods for better insight and contrast.

2.2.1 Lamp performance

In order to harmonise lamp performance, standards have been put forward from the early days of the incandescent lamp. Today standards have increasingly important role as new technologies and solutions have emerged on the market. Requirements for domestic incandescent lamps were covered in standard IEC 64, last updated in 1987, that basically also set a framework for other more recent performance standards [29]. A relevant standard was also released in 1988 for self-ballasted compact fluorescent lamp performance (IEC 969) [30]. The emergence of LED lamps in early 2000s, however, posed a new challenge because LEDs were fundamentally different from any previous light sources. The existing standards only applied to LED lamps in terms of general electrical safety and EMC, so a new set of standards was needed to cover LED lamp performance.

In relation to lamp performance, standard IEC/PAS 62612 was published shortly after the EcoDesign directive came to effect [11]. The standard describes mechanical, electrical and photometric performance requirements and test conditions. Table 6 presents electrical and mechanical requirements according to IEC 62612.

Table 6: Electric and mechanical requirements by IEC/PAS 62612 [11].

Lamp parameter	Testing conditions	Requirements	Notes
Dimensions	Detailed requirements in IEC 60630	Shall comply to IEC 60630	Typical A60 (A19 in imperial unit system) form factor D = 60mm, L < 110mm
Cap	Detailed requirements in IEC 62560	Shall comply to IEC 62560	E27, stands for Edison screw 27mm, comes with 27mm outer diameter, tolerances defined in the standards
Lamp wattage	Approved methodology*	Real wattage < rated wattage +15%	No low limit given
Luminous flux	Draught-free room at 25±1°C, max 65% humidity.	>90% of rated luminous flux	No high limit given
CRI	Measured at 0h and 25% of rated life	Values initial and 25% of rated life shall not have decreased more than 5 points from rated value	The aged value is either 25% of rated life or 6000h, whichever comes first.
Correlated colour temperature (CCT)		Tolerances defined for different CCTs presented by table 3.	Recommended CCTs 2700K, 3000K, 3500K, 4000K, 5000K and 6000K
Lamp life	Combination of lumen maintenance and ballast life		
Lumen maintenance	Luminous flux is measured at minimum of 1000 h intervals from initial to 25% of rated life.	Lamps are tested for L50 or L70 (50% or 70% of initial flux) at the final data point. Lumen degradation of more than 70% (50%) is considered a failure	Maximum duration of the test is 6000 h. Lamps are arranged into categories by lumen maintenance (table 7).
Endurance testing	**Thermal shock:** Non-energised lamp is stored at -10C for 1h, after which it is moved into heated cabinet at 50C for one hour. Cycle is repeated five times	Lamp must turn on and operate for 15 minutes after the cycling tests	
	Supply voltage switching: Test lamp is switched on and off for 30s. The cycling is repeated for a number equal to half of the lamp rated life in hours.		

This thesis mainly focuses on lamp ageing in the terms of lumen maintenance, colour stability. However, the standard only specifies testing for 25% of nominal lifetime of the lamp with lumen maintenance categories from A to E in 10% intervals, as can be seen from table 7.

Table 7: Lumen maintenance categories by IEC/PAS 62612 [11].

Luminous flux decrease at 6000 h or 25% of nominal lifetime as percentage of 0 h value	ΔΦ category
Measured flux decreased by no more than 10% of rated flux	Cat A
Measured flux decreased by no more than 20% of rated flux	Cat B
Measured flux decreased by no more than 30% of rated flux	Cat C
Measured flux decreased by no more than 40% of rated flux	Cat D
Measured flux decreased by no more than 50% of rated flux	Cat E

However, the standard does not provide any extrapolation method for estimating lamp lifetime beyond 6000 hours. Estimation of lamp lifetime is no doubt a complex process due to great variation in LEDs themselves as well as lamp technologies. An industry-approved method for estimation would undoubtedly simplify this process.

The focus of the thesis thus shifted into looking for approved methods, this time from USA, which has a long experience of product testing and market validation. However, as with the IEC 62612, the approved methods LM-79-08 LM-80-08 of Illuminating Engineering society (IES) only turned out to provide methodology for measuring and analysing existing data, not extrapolation. Further research revealed IESNA Technical Memorandum 21-11 (TM-21-11), which does specify how to extrapolate lumen maintenance data acquired according to LM-80-08 [31]. This memorandum was mainly created to allow product testing for EPA Energy Star rating presented in 2.1.4. However, LM-80-08 and thus also TM-21 only specify methods for measuring LED components and modules, not lamps or luminaires. Detailed analysis of LED lamp failure modes, presented in chapter 3.2, introduces other factors contributing to ageing and failure of the whole lamp. However, as lumen degradation of individual LEDs is nevertheless a major contributing factor in the total lamp lifetime, the method could be used in estimation.

Another important factor is colour stability over time, an issue especially prominent with multi-chip approaches presented in chapter 3.3. The IEC 62612 only divides lamps into eight categories depending on the colour deviation from rated value. The categorisation of lamps by colour and colour temperature stability is left for the manufacturer to specify. Related to colour and CCT, maximum CRI Ra deviation is also defined as can be seen from table 6. However, the colour science has remarked several problems with the CRI metric, implying possible change in near future [32] [33] [34].

2.2.2 Electrical safety

According to the Finnish chemical and safety agency (TUKES), electrical safety issues are the most common reason for market withdrawal for LED lamps [35] [36] [37]. Electrical safety issues are the most prominent with, but not limited to, LED lamps with metal heat-sinks.

The greatest risk comes in form of an electric shock. Due to the structure of the commonly used lamp sockets, such as E27 and B22, protective earthing is not possible and thus a double insulation of the lamp is typically required. The industry standards define insulation thickness and creepage distances on circuit boards and other live parts of the circuitry. European Standard EN 61347-1 defines safety requirements for lamp control gear [38]. The scope of the standard exceeds to both DC and AC applications from 0 to 250 V DC and $<$1000 V AC at 50 or 60 Hz. Thus, household lamps fall under the requirements of the standard.

It has been noted by safety agencies that LED lamps most typically suffer from insufficient insulation between live parts and the metal heat-sink. Depending on severity of deficiency, some lamps have been banned from market and others ordered for withdrawal. The problem seems especially pronounced in LED lamps manufactured by companies outside of the EU. Rapid Exchange of Information System for non-food dangerous Products (RAPEX) maintains a list of dangerous products union-wide [39].

2.2.3 EMC and EMI

The incandescent lamp has very simple electrical load characteristics, akin to nothing more than a resistor. However, modern retrofit lamps require a ballast or driver to operate directly from mains. Typically these electrical interfacing devices carry some form of switching mode power supply, making them prone to produce and induce electrical and electromagnetic interference (EMI). In addition, being based on semiconductor electronics, these devices are also sensitive to external interference such as voltage spikes, static discharges and EMI. Electromagnetic Compatibility (EMC) issues can be roughly divided into two distinct problems: conducted and emitted interference. Conducted interference is related to both harmonic and high-frequency voltages and currents drawn by the load as well as power factor in mains-supplied loads. In order to minimise the impact of retrofit lamps to the electrical networks and vice versa, the industry developed standards to establish limits for created and tolerated interference.

Inside the EU, no conducted interference limits apply for lamp with electrical power less than 25W [40]. This is mainly due to very low operating currents of these products, that aren't expected to cause problems in the mains network. Thus, most LED lamps are outside the scope of the conducted limitation. For radio interference, however, the situation is different. Recently, the rapid alert system (RAPEX) has issued warnings about LED lights manufactured in China. Some products have since been banned or withdrawn from the market due to high EMI emissions [41] [42].

3 Lamp technology

3.1 Incandescent lamp

Whilst the term 'retrofit lamp' refers to lamps replacing the traditional incandescent lamp or informally 'light-bulb', this study recognised a need to establish a reference to shed light onto what is required of a retrofit lamp. For longest time, the incandescent lamp was the only practical electrical light source for households and as such, it dictated the design constraints of luminaires from shape and dimensions to materials used. Thus, an introduction to this now abolished light source is justified.

Typical incandescent lamp consists of an Edison screw connector and thin glass envelope, from which air has been evacuated and replaced by inert gas such as argon. The glass envelope of the lamp can be clear or diffused (frosted); whilst the diffused envelope reduces glare, it also reduces lamp efficacy slightly. Inside the envelope a glass retainer supports a filament most typically made of tungsten alloy wire. An electric current heats the filament to high temperature where it glows and emits infra-red and visible radiation. One of the most typical form-factors for an incandescent lamp is A60. As the name might imply, it has an envelope diameter of 60mm and length of 100mm. These common dimensions have had some implications on design of many luminaires. A typical specimen weighs around 25-30 grams only, which is especially important in luminaires such as balanced-arm table luminaires. Figure 3 presents a structural schematic of a typical A60 incandescent lamp.

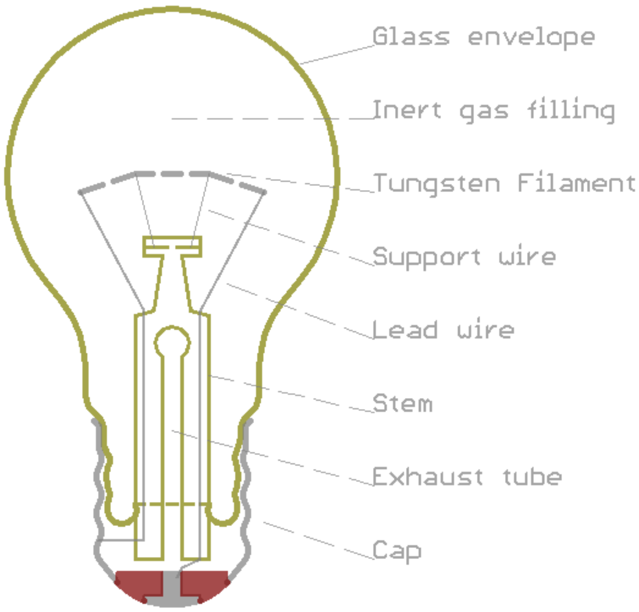

Figure 3: Slice-through schematic of a typical pear-shaped 60mm (A60) incandescent light-bulb.

Incandescent lamps have relatively low luminous efficacy of 10 to 15 lm/W, according to textbooks and test reports, as well as reference measurements conducted by this thesis [43]. This is mainly due to high infra-red content in the spectrum.

The filament of the lamp cannot be heated beyond its melting temperature, which imposes natural limit for the efficiency. Typical operating temperature of a tungsten filament is 2600-2700 K. The temperature of the filament is not always uniform, however, and thus local hot-spots will form where the tungsten starts to evaporate. Most of the evaporated tungsten ends up on the glass envelope, which results into darkening and decrease of light output [43].

The spectral power distribution (SPD) of an incandescent lamp is rather uniform, sloping down from red to blue. In effect it is very close to the Planck (black-body) radiator of the same colour temperature. Because these radiators are also used as a reference when calculating the general colour rendering index (CRI), the incandescent lamp receives a nigh-perfect score of 99 or more for the Ra number. This doesn't, however, necessarily mean the light would be preferred by users, but the index is still widely used in lamp package markings. Recent studies have indicated that user preference is much more complicated than mere colour fidelity. As such, the CRI metric should be considered outdated and might be subject to change in following years [32] [33] [34].

Incandescent lamps can be characterised as point sources, also implied by the structure in figure 3. They radiate equally on all directions short of the socket, and thus many luminaires incorporate a reflector in the design. The near-uniform luminous intensity distribution can also be used for an artistic effect in luminaires, illuminating a decorative shade in a floor lamp or the crystals in a chandelier.

Using incandescent light-bulb was easy for the consumers, since it could directly run on mains AC voltage without external transformers or ballasts. As a load, incandescent lamp behaves much like a resistor, thus only consumes active power. The power factor is thus high. When cold, the resistance of the filament is low, and thus a higher warm-up current runs for the fraction of a second it takes for the filament to heat up and start to glow. In many cases this inrush current is what kills the lamp: local hot spots can reach melting temperature and split the filament. Because of its simple load characteristics, a lamp can be easily dimmed with transistor or TRIAC chopper circuits, also known as incandescent lamp dimmers. A notable feature of a dimmed incandescent lamp is the reduced colour temperature. The colour of the lamp turns more reddish when it is dimmed down, creating an effect consumers have learned to expect from the lamp. This property has been used for artistic effect in chandeliers in the past [51].

Albeit its many remarkable properties, the incandescent lamp has all but faded into obscurity by ever stricter efficiency requirements. Incandescent lamp could, at its best, reach energy class D. This implied complete prohibition of imports and placement on the market in 2012, as discussed in chapter 2.

3.2 Halogen retrofit lamp

Halogen lamp is a development of the incandescent lamp, employing halogen gas cycle in order to increase the lifetime of the lamp. Halogen gas filling inside the lamp envelope returns some of the evaporated tungsten back to the hot spots of the filament, reducing glass darkening and filament erosion. As a result, the temperature of the halogen lamp filament can be higher than in regular incandescent lamp. This, in turn, results into luminous efficacy of 15-25 lm/W [43].

Figure 4: A typical B-class halogen retrofit. The lamp includes internal transformer and a low-voltage halogen lamp with infra-red reflective coating.

Halogen retrofit lamps exist in two basic configurations. The first configuration is a direct mains voltage lamp, and the other has an internal transformer which converts the mains voltage to low voltage of 12 V AC. In order to achieve required efficacies, different methods can be used to further increase lamp performance by decreasing the heat loss from the filament. The lamp can use less thermally conductive filling gas, such as xenon, which can improve efficacies up to 20% [4]. Designers have also employed special IR-reflective coatings on the glass envelope. These coatings reflect part of the infra-red radiation back inside the lamp, retaining filament temperature with less electrical power consumed [44]. This method can increase efficiency up to 40% and enable the lamp to reach energy class B, but is only possible for low voltage halogen lamps due to length of the filament [26]. The power of a low voltage halogen retrofit is limited by the internal transformer heating and thus it is difficult to find lamps for replacing incandescent lamp powers greater than 60W.

As discussed in chapter 2, practically all halogen lamps excluding some special purpose units will be placed under import and manufacture prohibition in 2016. Thus, the halogen lamp will eventually disappear from the market, being only little better than incandescent lamp in terms of energy consumption.

3.3 Compact Fluorescent Lamp

Compact fluorescent lamp (CFL) was developed as a direct replacement to a contemporary incandescent lamp as a response to the oil crisis in 1970s. Many separate developments led to General Electrics engineer Edward Hammers spiral tube fluorescent lamp in 1976 and eventual commercialisation of folded tube lamp with integrated ballast by Philips in 1980 [45]. [46]. Throughout its existence, the basic structure of the CFL has remained remarkably similar, but the technology and efficiency has improved significantly. There are basically two different types of CFL: one with external ballast and another with integrated ballast. This thesis focuses solely on the integrated type of CFL from here on. Figure 5 presents the basic structure of a typical screw-base tubular CFL.

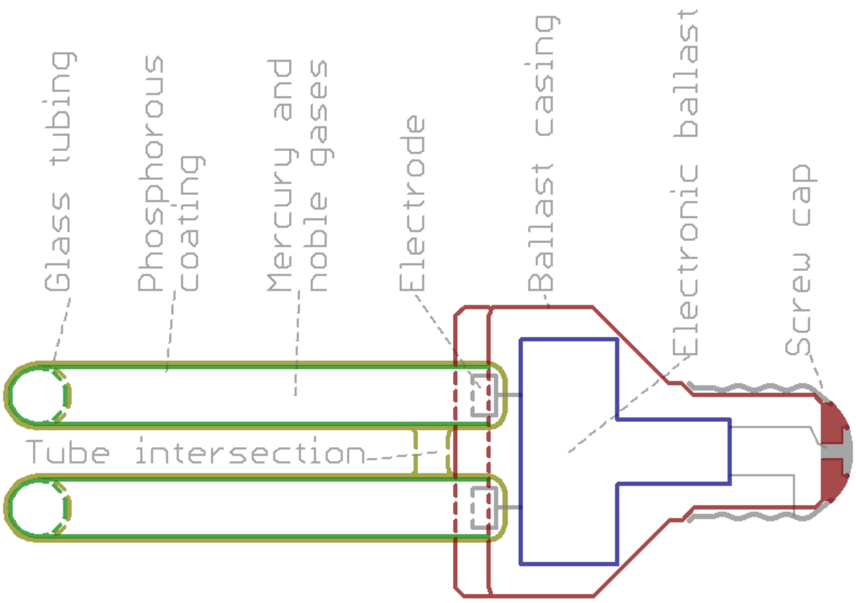

Figure 5: Slice-through schematic of a tubular CFL.

A modern CFL consists of electronic ballast built into the lamp cap and twisted or coiled fluorescent tube. The fluorescent tube generates visible light from electric discharge through multitude of processes. First of all, the tube contains mercury vapour which, excited by the discharge, emits mostly ultraviolet and visible light. The ultra-violet part of the spectrum is converted into visible by phosphor coating inside the tube. The phosphor output amounts to almost 90% of the total light output [43] [47].

The mercury vapour pressure is critical for the efficient operation of a CFL. This implies operating temperature has a large impact on the operation of such lamp. Thus, when a CFL is switched on, it requires some time for the vapour pressure to reach optimal levels. This starting time can range from a few seconds to several minutes. Some CFL use mercury amalgam to reduce the effect of temperature. The amalgam regulates the mercury vapour pressure, but also slows down the starting time. An auxiliary amalgam placed close to the lamp electrodes speeds up the process considerably [48]. In cold environments, such as outdoors, the CFL rapidly loses efficacy and may have difficulties in starting up properly.

CFL electrodes are a vital component, between which the electric arc occurs. The electrodes are typically coated with substances that increase electron emission and facilitate start-up. The electrodes also require some heating by the electronic ballast before they are able to strike the arc. The ballast can also increase the arc voltage for faster start-up, but this has a detrimental effect on emission coatings. All in all, electrodes are the weakness of the CFL, dictating the amount of start-up cycles the lamp can handle. After most of the emission coating has worn off, the lamp simply fails to start [47] [43]. Even without electrode failure, the practical lifetime of a CFL remains around 8000-15000 hours. This is mostly due to depreciation of luminous output through phosphor degradation and formation of inactive deposits inside the fluorescent tube. [4]

The light output of CFL is roughly proportional to the emissive area. The shape and orientation of the emissive tube surface dictates the luminous intensity distribution, which in many cases is rather side-emitting. This does have some implications on luminaire design. For instance in target- and spot-lights require reflectors to direct the CFL light. Floor-lamps are typically not the perfect application for CFL because most of the side-emission is absorbed by the lamp shade. Furthermore, part of the light in CFL is emitted inwards to the bundle of tubes, causing some loss due to internal reflection and absorption. In relatively low powers, the fluorescent tube can also be encased in a secondary glass envelope, which gives the lamp more traditional, bulbous appearance. This extra dome somewhat levels out the luminous intensity distribution, but does introduce additional losses.

Figure 6: The most common types of CFL from left to right: Tubular, Helical (spiral) and domed (enveloped). Source: Osram.

As implied by the operating principle, the spectral power distribution of the CFL consists of visible mercury emission spikes and broader phosphor emissions converted from the ultraviolet discharge. This generates the familiar, spiny spectrum of the CFL. Due to deficiencies and discontinuities in the spectrum, colour rendering and light quality remain moderate.

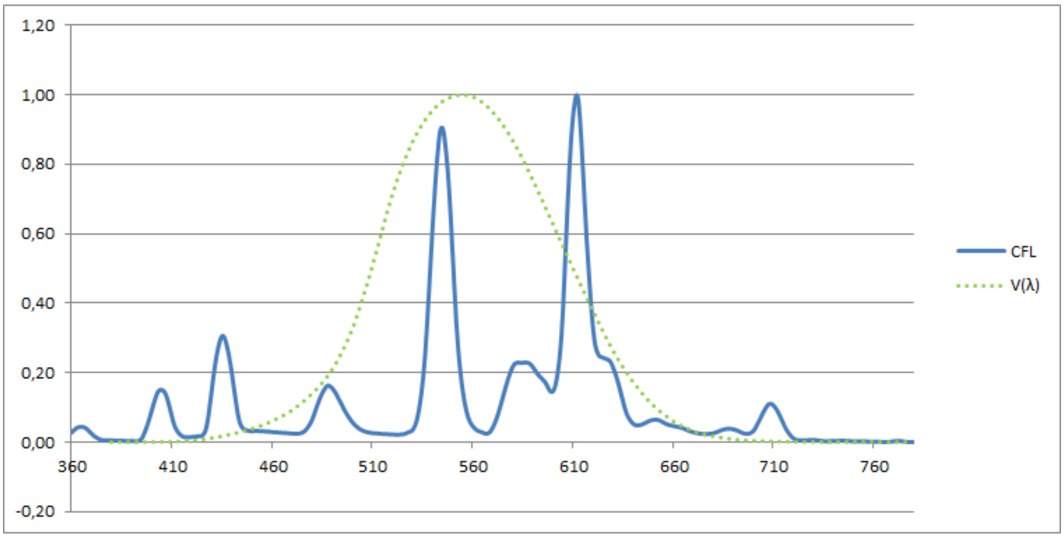

Figure 7: Spectrum of a typical 3000K retrofit CFL and human eye spectral sensitivity curve V(λ) (dotted line).

The luminous efficacy of the modern, entry-level CFL is around 50-70 lm/W according to measurements conducted. This makes the CFL three to five times more efficient than comparable incandescent lamp. Because the phosphor mixture of the lamp can be controlled during manufacturing, the CFL is also available in wide range of hues and correlated colour temperatures (CCTs). However, in most cases the colour coordinates aren't exactly aligned to the Planckian locus and the light from the CFL is viewed as artificial or at least unnatural [49].

Most CFL are not compatible with incandescent lamp dimmers due to properties of the electrical ballast and the fluorescent tube. Fluorescent tubes themselves can be dimmed by controlling the arc current, but this requires a special ballast circuitry and exists as a rather expensive niche solution. A CFL can only be dimmed to about 20% of the full luminous flux, after which the electrode voltage is too low to maintain the electric arc [50]. It should also be noted that unlike the incandescent lamp, the colour of the CFL does not change with dimming. This is a shortcoming for decorative solutions as people are accustomed for the colour temperature shift attributed to the incandescent lamp [51]. The power factor of a CFL is typically rather poor, around 0.5-0.7 capacitive. In addition, Harmonic currents and EMI from the ballast can also be an issue. Because the lamp powers are typically rather low, this doesn't pose a problem for the mains network. CFL with high power factor are available, but are more expensive and less efficient due to more complicated ballast electronics.

It has been noted by many sources that the lighting industry has been investing heavily into development of the LED instead of CFL during recent years [52]. It can thus be seen that whilst LED lamps are developing very rapidly, the lack of new development on CFL is finally going to marginalise it as potential replacement. In many cases this is probably by design, as industry makes a shift for LEDs [2].

3.4 LED lamp

LED technology has existed several decades, mostly as indicator lamps. Since the invention of efficient blue LED by Shuji Nakamura in 1993, lighting applications based on blue LED have started to appear. The development of the LED manufacturing processes has been incredibly rapid from the early, low-power retrofit lamps in 2003 to the latest high power LED luminaires that surpass even the CFL in efficacy. Even at the time of writing, the LEDs are developing at extraordinary pace and thus the latest efficacy figures are hard to state. Furthermore, as this thesis mainly focuses on LEDs, a detailed introduction on LEDs in lighting applications seems justified.

3.4.1 Properties of LEDs

An LED is based on a semiconductor component, which produces mostly visible photons from electron-hole recombination in the semi-conductive junction. The light produced by semi-conductive LED chip is relatively monochromatic. Unlike its incandescent or fluorescent counterparts, LED is completely solid-state, implying greater stability and unmatched structural robustness. The lifetime of an LED can thus be extremely long, sometimes referred to in tens of thousands of hours. A single LED chip operates at low voltage, which offers the designer some flexibility and also facilitates low-voltage applications such as battery powered lamps. In recent years the conversion efficiency or 'wall-plug' efficiency (e.g. Conversion of electrical watts to radiometric watts) has been increasing steadily, now exceeding 70% [53]. LED chips are enclosed into special casings with lead wires and primary optics. The primary optics often comprises a lens and several coatings to increase light output through reducing of losses from total internal reflection.

LEDs, as many other semiconductors, are sensitive to overheating, and thus the removal of excess heat is important. Not only is overheating a problem, but the luminous efficacy of an LED also declines rapidly with rising junction temperature [54]. As a result, high power LEDs require aptly designed heat-sink to maintain safe junction temperature. Cooling is a serious concern in compact high-power LED lamps where the power density can be rather high. The requirement for thermal management has great implications on LED lamp structure, weight and price. However, the recent increases in efficiency has alleviated this drawback to great extent and made ever higher luminous outputs feasible in recent years.

3.4.2 White LEDs

In general lighting applications, it is sensible to emphasise on white LED (WLED). White LEDs can be created in a multitude of ways. First white LEDs used three or more single-colour emitters, typically red, green and blue, which were mixed using secondary optics. The immediate challenge with such emitter was finding a correct balance between different colours and managing that balance over full operating temperature. Different LED colours use differing semiconductor chemistries, which makes them react dissimilarly to changes in temperature. This suggests an active feedback controller would be needed, which increases cost and is not feasible for an LED lamp as such [55].

The most widely used method by far for white LED is the phosphor conversion. Phosphor-converted white LEDs (PCWLEDs) use radiation from a blue LED chip to excite a series of phosphors, which then emit light in the green-red range of the visible spectrum. This phenomenon, referred to as the Stokes shift, is actually the same at work in a fluorescent lamp. Excited by blue LED chip instead of ultraviolet light, white LED phosphors have much smaller amount of wavelength shift. Stokes shift efficiency can simply be calculated as ratio of exciting and emitted wavelengths. By the use of multiple phosphors, the colour temperature and -quality of the PCWLED can be controlled to a great extent. At its best, a good quality PCWLED can offer almost incandescent-like light with Ra value at 95 points or more. However, subjective colour quality or preference aren't that easy to determine and might not be the best possible [34]. Due to one-chip construction, the colour stability PCWLED is easy to manage and no special feedback circuitry is needed. The drawback of phosphor conversion resides in generating the red part of the spectrum (600-700nm), where the stokes shift losses are the greatest. Furthermore, because of the broad emission of the red phosphor, some of the light is emitted in the far red or near infra-red region, where it contributes little to the luminous output.

Another white LED solution was proposed by several studies and introduced by Cree and Osram in TrueWhite and Brilliant Mix technologies, respectively [56] [57]. The technique basically mixes a blue LED with green phosphor and an efficient red LED, which provides the red component to the spectrum. Due to several different LEDs used, this technology is sometimes referred to as quasi-multichip, semi-multichip or PCWLED+R (Where R stands for red) since it also includes phosphor emission. The resulting SPD has basically two spikes with broader emission hump amidst them, with rapid cut-off at borders of the V(λ) curve. At least in theory, this makes the luminous efficacy of the spectrum high, since little to no non-visible radiation is generated. In terms of colour quality, CRI Ra values can reportedly exceed 90 points [57]. The subjective colour quality remains to be determined as of 2013 [34].

One clear drawback of the multi-chip technique is having to drive two (or more) LED chips with different chemistries and differing temperature and ageing characteristics. For good colour stability, an active feedback driver would be needed, although the problem isn't as pronounced as it is with multi-colour LEDs [58]. In some commercial products the LEDs are simply connected in series, without bothering any form of feedback. This basically means the colour coordinates will only meet the Planckian locus at certain operating conditions, as observed during the measurements. Figure 8 presents the spectra of white LEDs using different technologies whilst figure 9 presents two LED modules utilising the above-mentioned phosphor techniques, respectively.

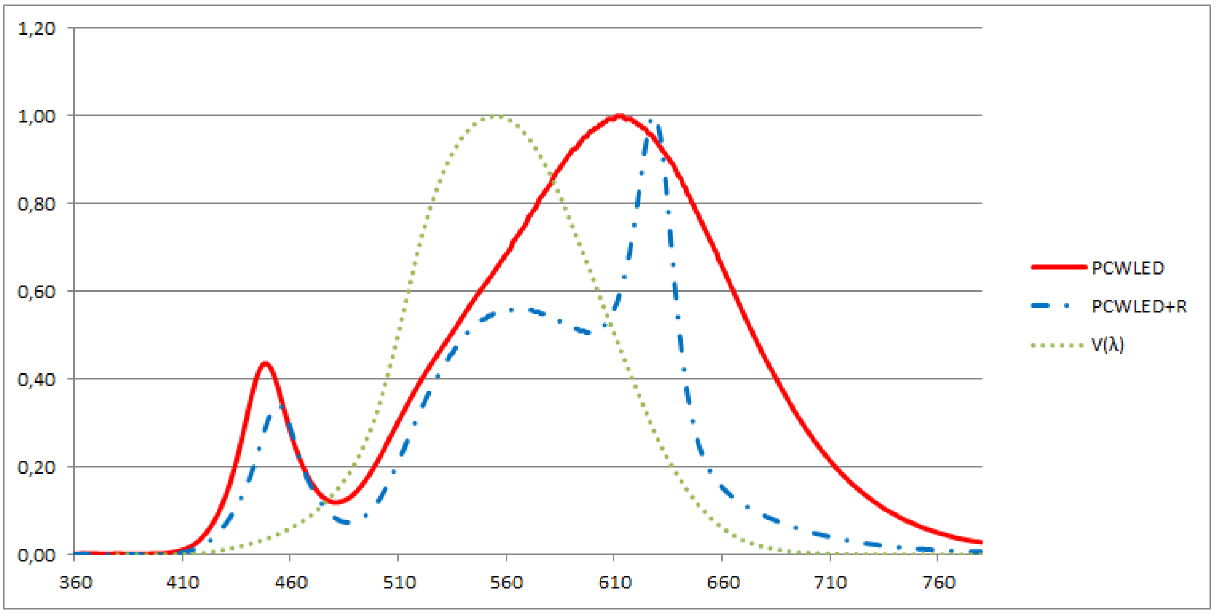

Figure 8: Typical SPDs of PCWLED (solid line), PCWLED+R (dash-dot line) and human eye spectral sensitivity curve V(λ) (dotted line).

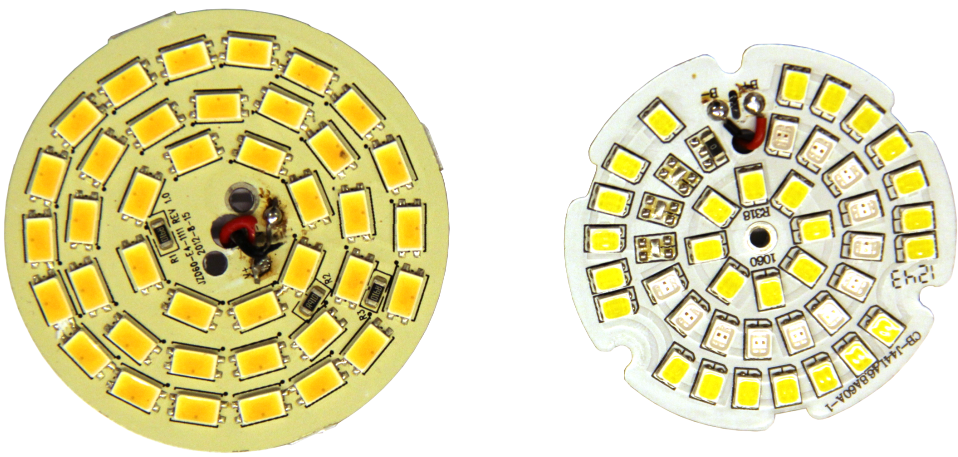

Figure 9: LED modules from 800lm retrofit lamps. left: Dual phosphor PCWLED, right: PCWLED+R. Note the different LED colouration as the second module has no red phosphor in the white LEDs.

Colour parameters of LEDs are generally good, and still subject to improvement. The most typical CCT value for LED products in Europe resides around 2700 K, mimicking the incandescent archetype. Some LEDs are also available for higher colour temperatures of 3000-5000 K. With LEDs, the technology itself is not really a limitation, but the colour temperatures available are based upon estimated user preference and sometimes efficacy requirements.

3.4.3 LED retrofit lamps

LED lamps, the main focus of the thesis, are a niche application of mid- to high power LEDs. This thesis especially focuses on LED lamps aimed to replacement of Edison-screw incandescent lamps. However, the information is also applicable for other cap types. Whilst in 2010, LED lamps were still an upcoming technology with only a few models available, variety of such lamps has increased rapidly in recent years [4]. A typical LED retrofit lamp consists of three basic components: The LED module itself, the LED driver and the lamp body. Lamp body components can once more be divided into the cap, driver mounting and insulation, heatsink and secondary optics (typically a diffused dome or envelope). Unlike an incandescent lamp, LED lamps are typically rather heavy due to the heat-sink. This may complicate their use in some luminaires, as discussed in chapter 3.1. Figure 10 presents a structural schematic of the most common type of LED lamp available: the hemisphere domed LED lamp.

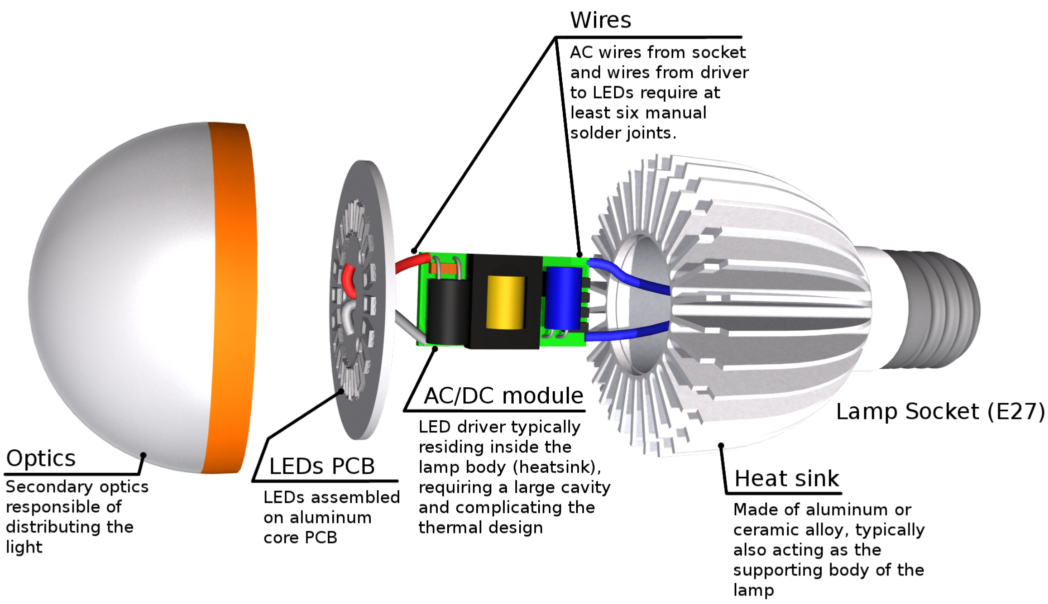

Figure 10: Exploded schematic view of a typical hemisphere-dome LED retrofit lamp.

The structure and orientation of the LED emitters dictates the luminous intensity distribution from an LED lamp. In the case of figure 10, the hemispherical dome makes the luminous intensity distribution rather directional along the axis of the lamp. This quality can undoubtedly be very useful in applications requiring directional light, such as spotlights, downlights and other luminaires that would traditionally require a reflector. However, because the distribution of light of an LED lamp differs greatly from that of an incandescent, LEDs face difficult time illuminating applications such as floor-lamps and decorative luminaires in general. Some special LED lamps do exists, however, where the distribution of light is modified through use of different LED arrangement, secondary optics or remote phosphors.

These niche solutions are typically more expensive, however [59].

The LED driver is typically a switched-mode power supply (SMPS), driving the LEDs with constant current rectified from the mains. As with most rectified power sources and not unlike CFL ballasts, the power factor of a typical LED driver is around 0.5...0.7 capacitive. This also makes operation with incandescent lamp dimmers challenging, requiring special circuitry. Thus, many LED lamps on the market today cannot be dimmed, although it could be argued even further energy savings could be made by dimming. Some high-end LED lamps can be dimmed with TRIAC and boast high power factors of 0.9 or more. However, the typical efficacies of such lamps are lower due to more complicated driver and consequently poorer efficiency. As with CFL, the colour temperature of an LED lamp does not change with dimming, unlike the incandescent lamp reference. It could be noted that the PCWLED+R technique introduced briefly in chapter 3.4.2 could offer a solution for this. However, a special driver would be needed to accomplish this, likely increasing the price of the lamp also [51].

LED lamps do not suffer from the start up delay present in CFL and are less sensitive to low ambient temperatures than even amalgam CFL. According to Premiumlight.eu, LED lamps are also much more suitable for outdoor use than their CFL counterparts [60] [61].

The future of the LED is bright with little doubt. The LED is the only light source that has been rapidly developing during the recent years, and in many cases the rapid development has surprised researchers and industrial designers alike. LED is aggressively competing for a market share and the prices of LED lamps are decreasing along with developing manufacturing processes and new innovation. By 2013, it became clear to lighting professionals that LED is, without a doubt, the light source of the future [63] [64]. How long the traditional lamp with socket will prevail, remains to be seen, however.

3.5 LED lamp failure modes

As discussed previously, the luminous flux of LEDs degrades over time, which is one of the reasons the requirements for LEDs initial luminous flux is made higher than CFL in European commission regulations. The lifetime of an LED lamp is typically defined by its L70 value [11], which basically means that the lamp is at an end of its usable life when its luminous flux has degraded down to 70% of initial. For 60 W equivalent lamps this translates into 564,2 lm of the required, initial 806lm [1].

However, since LED lamps consist of more than just the LEDs, other failure modes have to be taken into account [71] [10]. Ageing of the LED chip results from several degradation mechanisms. These mechanisms include photometric damage, localised heating due to uneven electric current distribution and thermal shock due to overheating [66] [67] [68]. The chip ageing results in reduced efficiency and thus less emitted light for the same input power. High operating temperature speeds up ageing, shortening LED lifetime.

Notably, an LED can also fail completely, instead of just degrading. The two types of failures here include open and short circuit. Open circuit results from a failed bonding wire or junction, and render a series of LEDs dark as current can no longer pass through the series. Some LEDs use a flip-chip construction where bonding wires are not required and thus cannot fail as an open circuit [69]. A shorted LED can still conduct electricity for other LEDs in the series, but it can render parallel LEDs dark as it shunts the current. Indeed, this thesis observed that either series or series-parallel LED wiring was used in the LED lamps studied. This would imply a partial or complete lamp failure in the case of a single failed LED.

In addition to LED chip itself, both the phosphors and optical materials degrade. The phosphor degradation which impairs the conversion efficacy, is brought about by both thermal and optical damage [70]. Because the phosphor typically emits yellow and red light, its degradation has a distinct effect of shifting the colour coordinates towards blue. This effect could be followed in the ageing test conducted by this thesis. Degradation of primary and secondary LED optics can reduce transmissivity as well as cause hue changes due to discolouration [67] [68]. Plastic optics are especially prone to ageing, including possible tertiary optics such as plastic lamp domes. Reduced transmissivity was characterised practically indistinguishable from LED degradation.

Using LEDs in a lamp introduces yet another major failure mode. An LED lamp includes a driver which, as an electronic device, has a limited service life. The driver consists of many electronic components, of which electrolytic capacitors are most prone to failure due to electrolyte boil-off in high temperatures [10]. LED lamp driver typically fails completely, instead of simply diminishing power output. To determine cause for failure, a post mortem was also performed to lamps that failed completely during testing. Finding the distribution of failures would require a relatively large sample and thus would not be reliably achieved in the test conducted by this thesis. To give an example however, figure 11 presents distribution of failures in outdoor luminaires.

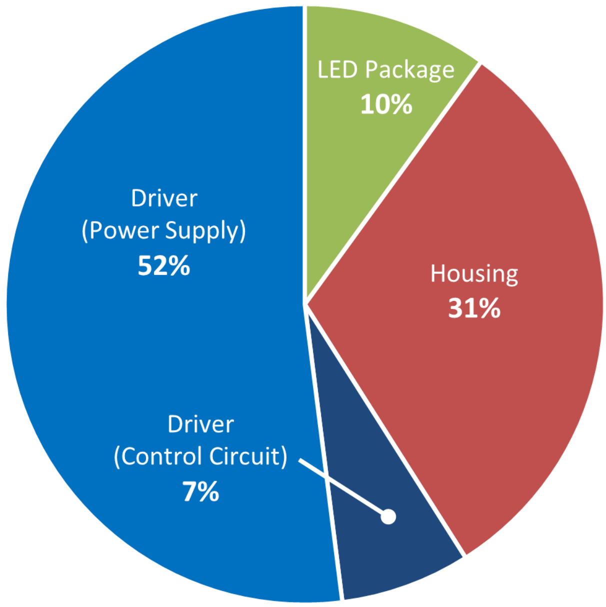

Figure 11: The distribution of failures over 34 million operating hours for one manufacturer's family of outdoor luminaires. A total of 29 fixtures failed out of more than 5,400 (0.56%). Source: Appalachian Lighting Systems, Inc. [71]

Against this background it is obvious that even in an LED luminaire, drivers and other electronics contribute to the majority of failures. This proportion is probably even larger for LED lamps since the operating temperature inside the lamp is much higher. The failure rate of an LED product over time can be visualised by aptly named bathtub curve, presented by figure 12.

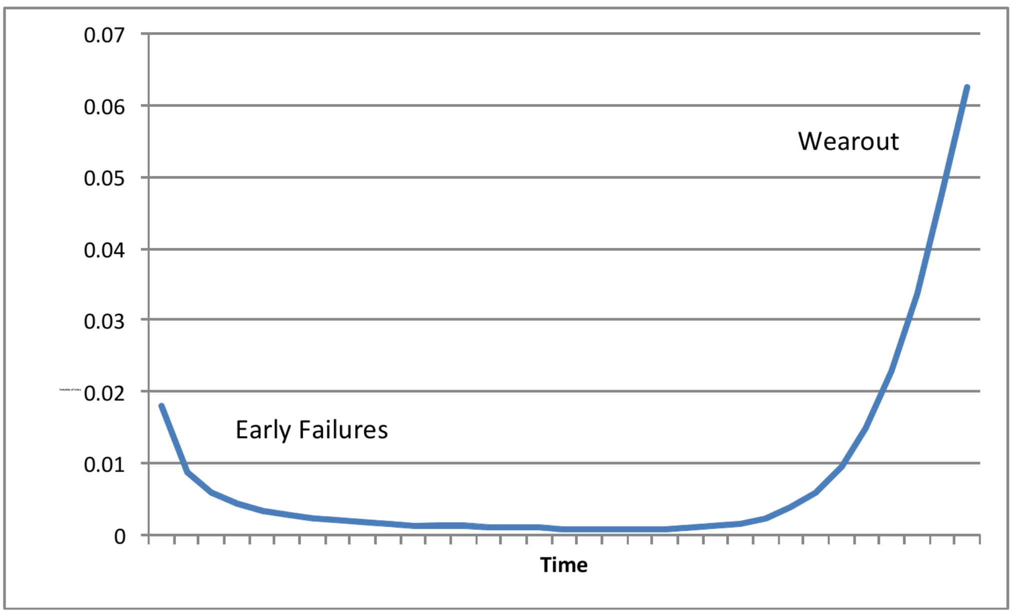

Figure 12: Distribution of total failures over time - the bathtub curve [10].

The initial spike accounts for early failures. This failure rate is highly dependent on the quality control by manufacturer, as these failures are caused by faulty or defective components that could have been detected by thorough quality monitoring process. The failure rate then decreases until the product ages closer to its nominal lifetime. Eventually, wearing out components increase the failure rate dramatically. These failures account for complete driver failures and lumen depreciation. However, as discussed earlier, driver failures are probably the more common failure mode and as such start increasing the total failure rate sooner than diminishing lumen output.

Against this background, this thesis proposed two different tests for scoping and estimating the lifetime of the lamps. An ageing test for lumen depreciation was to be conducted to determine the L70-values of the lamps and a switching test to stress the drivers. However, due to the time and cost limitations encountered, the thesis only conducted an 6000-hour L70-test as recommended by most of the standards. The next chapter reviews previous research and testing recommendations to find a suitable practice for measuring, reporting and analysing the results of the ageing test.

4 LED lamps in recent studies

This chapter reviews previous research and benchmarking work by predecessors, magazines and scientific studies in order to build up background information. Based on the previous work and a market survey conducted, the thesis selects LED retrofit lamps to be tested for photometric and electrical performance as well as longevity.

4.1 Benchmark studies

This section reviews some benchmark studies that were influential to this thesis. The list is far from comprehensible, but rather aims at providing the reader with an overall picture of LED lamp development in recent years.

4.1.1 Aalto University

The review and background study for this thesis begun from a work of a predecessor. In 2010 LED lamp was an emerging new technology and only few lamps and limited powers were available. Aalto University conducted similar study in his master's thesis [4]. In 2010, diffused incandescent lamps were already banned from being imported by EC 244/2009, introduced in chapter 2.1.2, and a new generation of retrofit lamps were flocking to the market. LED retrofit lamps had been around from early 2000s, but started to achieve CFL-like performance in 2010. However, LED lamps were only available to replace relatively low-power incandescent lamp, which surely limited their applications at the time.

The study also conducted a limited ageing test. The lamps were only tested for 2000 hours, however. Also, due to the lack of established extrapolation methods at the time, the lumen depreciation results were only displayed for the actual measured period. The results, however, display an interesting trend that suggests CFL lamp actually lost their luminous flux faster than LED lamps. Moreover, EC 244/2009 had a 85% lumen maintenance requirement for open CFL (tubular or spiral) and 80% for enveloped (domed) CFL at 2000 h of use in stage 1. Stage 5, entered in September 2013, has even stricter lumen maintenance requirements of 88 and 83%, respectively, as shown in table 2 of chapter 2.1.2.

The study also examined luminous intensity distribution of CFL and LED lamps of 2010 and simulated illumination results with different luminaires, including pendant, ceiling lamp with reflector, a decorative floor-lamp and table-lamp. A conclusion was that LED lamps of the time were most suitable for directional applications such as table-lamp. However, the thesis failed to take into account efficiency factors with different luminaires, nor did it mention resulting light output ratio (LOR) in each case. To summarise all findings, the Lighting Unit compiled a summary and guide for selecting household lamps [20].

4.1.2 Technical magazines

LED lamps have also been studied by lay-person magazines throughout recent years. The Finnish technology-oriented magazine Tekniikan Maailma published an LED lamp study in special number in October 2012 [6]. The study reviewed LED lamps of electrical powers between 4 and 11 Watts, thus falling slightly out of the scope of this thesis. Only two lamps in the study, V-light 10 W LED lamp and Energetic A60 11 W technically reached the 60 W retrofit category concerned in this thesis.

However, the review did not report the luminous flux and the methodology used was rather superficial. Furthermore, only one lamp per model was subjected to the test, making the results completely unreliable. Furthermore, the article falsely claims directional LED lamps would perform poorly in applications requiring directional light, only based on a photo of the reflector. Over all, the benchmark is rather disappointing as no usable photometric data is provided and the lamps themselves aren't comparable due to differing power classes.

Another noteworthy benchmark by Popular Mechanics subjected several incandescent, CFL and LED lamps to photometric and electrical tests and calculated energy costs per 1000 hours for each tested lamp. The article also collected subjective feedback from users in terms of light quality and usability of the tested lamps. However, only one of the tested LED lamps was available in Europe, and as such, the results aren't comparative. The reporting of technical data in the web article is also confusing and doesn't allow for easy comparison between different lamps. Furthermore, the article totally lacks a summary, publishing date and any analysis on the trends in the lighting industry [74].

The trend in popular magazines to report information poorly or unprofessionally is unfortunately common. Because these magazines are read by many consumers and the information that is provided is easily available, more care should be taken when reviewing the articles for publication.

4.1.3 Scientific lighting journals

Professional lighting journals typically have higher quality articles and benchmark tests on LED lamps due to professional researchers and equipment. Although LED lamp benchmarks aren't very common in these sort of magazines, this thesis considered one in particular as worth of mentioning. An article by Constantinos A. Bouroussis et. al. was published in Romanian journal Ingineria Illuminatului in 2012 [7]. While the article focused on LED retrofit lamps for directional GU10-socket for halogen spot lamp replacement, the layout and the information reported by the article was used as a model for this thesis. The article first introduces and characterises the tested GU10 retrofit LED lamps, presents the methodology used and finally analyses the results and evaluates the lamps. The same basic structure is followed in this thesis with E27 lamps.

As for the results of the article, it was already obvious LEDs would replace the GU-socket halogen spot-lamps in foreseeable future. The study reported luminous efficacies reaching 58 lm/W, which for 2012 is already a good result. Furthermore, CFL models for these small lamps do not exist due to the larger space requirement of the fluorescent tube and thus it would fall upon LED technology to fill the vacant ecological niche after the passing of the halogen lamp in 2016. The same trend had also been noted by semi-professional LEDs Magazine [64]

4.1.4 US Department of Energy

LED lamps have long been lauded as a real successor for the incandescent lamp in the United States. Thus, the United States Department of Energy (DOE) has been conducting market studies such as CALiPER (Commercially Available LED Product Evaluation and Reporting) ever since LED lamps were first introduced [72]. Remarkably, the DOE aim has been to inform the consumer by publishing easily apprehensible summaries of the findings in their fact sheets [65]. An example of the luminous efficacy of lamps sold in USA can be seen in figure 13.

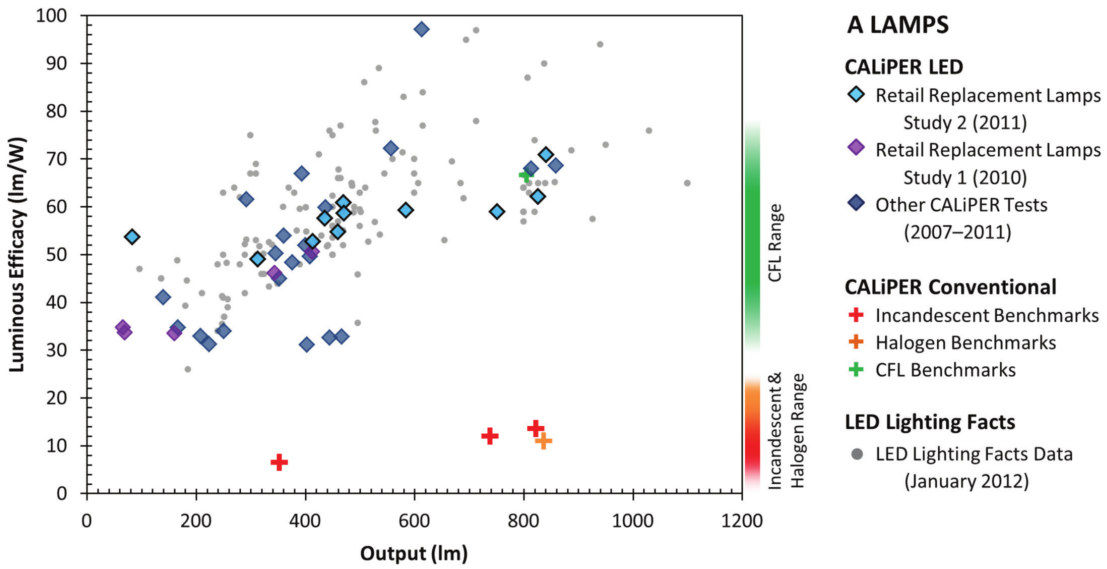

Figure 13: Discovered efficacies of CALiPER test results [65].

It is relatively easy to see that LED lamps were comparable to CFL in luminous efficacy already in 2011. This also implies the development of LEDs had been taken further in USA, probably due to stricter performance requirements such as Energy Star. The fact sheets also bring up the topic of non-standard angular distribution of luminous intensity in many LED lamps and the implications it may have in many luminaire applications. This will be discussed further in the results and conclusion of this thesis.

4.1.5 PremiumLight

The PremiumLight project aims to conduct similar benchmarking and informing work inside the European Union, perhaps as a response to US DOE work on the other side of the Atlantic Ocean. Carried out in partnership with 12 European organisation, the program has benchmarked LED lamps for several years and reported findings on their website [60].

This thesis reviewed the LED models tested by PremiumLight and its partners in order to find models that were not yet tested or reported on the site as well as models that were tested. According to the Finnish partner organisation, Motiva, an ageing test was also being conducted at the time of writing, but the results were not out as of yet. Some of the LED lamps tested by PremiumLight are also tested in this thesis, and it will be interesting to compare the ageing test results once released by the project. These models include Philips LED lightbulb and the more expensive Philips Master LED lamp.

4.2 Studies on lamp ageing

LED lamp ageing was initially recognised as an important aspect in the retrofit lamps. LED lifetime is important because it dictates the possible energy and cost savings over incandescent lamps and especially CFL. However, estimating LED chip or component lifetime based on previous studies is one thing, but measuring LED lamps, arranging an ageing test and analysing data is whole another. Since LED lamp is much more than just LEDs, the thesis needed to establish a wider perspective to lifetime of LEDs.

As discussed previously, the LED topic has been widely and thoroughly documented in USA. The US DOE, in alliance with lighting industry, published recommendations for LED luminaire lifetime testing and reporting in 2010 [10]. These recommendations recognised the important distinction between LED luminaire lifetime and mere lumen depreciation, as failures and colour properties would also have to be taken into account. The conclusion of the paper recommends a framework for reporting lumen maintenance and ageing data as well as bestows responsibility upon manufacturers to report their quality control and changes in manufacturing processes. It further recommends that the lighting facts package label should also include more detailed lifetime information, especially the L70/B50-pair.

Recommended methodologies have been reported and presented in many documents such as the one just presented. However, for the purposes of this thesis, applied methods were more interesting. Thus, the thesis also reviewed two studies related to LED lamp ageing. As testing periods for lumen depreciation were relatively long, it was interesting to find possible methodologies for accelerated ageing test. A paper published by Euramet subjected a group of LED lamps in both 45°C and 60°C elevated temperature test as well as room temperature test conducted by Mikes in February 2013 [15]. The findings were that acceleration factors up to 2.96 could be achieved with elevated temperature testing. However, the paper recommended minimum of 20 samples per lamp model and strict control on the climatic chamber. Due to the limitations imposed by both consumable and labour costs as well as available laboratory facilities, neither requirement could be met by this thesis. Thus, the idea of an accelerated ageing test for the lamps had to be abandoned. Notably though, the paper used and applied IES LM80-08 and TM-21-11 methodology for testing LED lamps, not just LED chips. This provides some validation on the usage of the TM-21 extrapolation methodology in this thesis as well.

Lumen maintenance data, on the other hand, is scantly available. Lamp manufacturers seem to have a tendency to test their products internally and keeping the information to themselves. Furthermore, Solid-State Lighting (SSL) has seen little long-term tests to verify lumen maintenance predictions. However, a study conducted by US DOE actually tested a series of lamps for 25000 hours under standardised conditions [14]. The testing was started in September 2009, continued till July 2013 and monitored lumen depreciation of 200 specimen. The lamp tested was non-other than the Philips L-price entry model [73]. Not only did the test confirm commendable lumen maintenance on the part of the L-price winner, the analysis of the results also validated TM-21 projection methodology to an extent. It also demonstrated an important aspect related to LED lamps: A good-quality, well designed LED lamp can operate reliably for many years and live up to nominal lifetime promises. This is a significant outcome since it actually motivates testing the LED lamp longevity and encourages publishing the extrapolation results.

4.3 Market survey

The thesis surveyed the existing domestic market of LED lamps and scoped interesting models for testing. The survey was conducted through catalogues and web-stores of well-known supermarket chains and hardware stores as well as fieldwork. The fieldwork also included information gathering and interviewing salespersons to superficially scope the sales and most popular LED lamps in the selections of the shops. As it turned out, the variety of LED lamps has increased almost exponentially in recent years, and as discussed in the Introduction, there was a clear need to limit the size of the test group in several ways.

First, only lamps capable of 60 W incandescent replacement were selected due to recent developments and increase of LED retrofits in 60 W equivalent powers. In fact, a total of 14 different lamps were eventually selected to the test, based on another important criterion, availability to the consumer.

Availability was the most important criteria of selection. Although interesting from technical viewpoint, it made little sense to select some of the more exotic lamp designs as these were only available through rather complicated on-line purchase procedures, something only the keenest of consumers could be expected to follow through. The importer would also be responsible of the electrical safety of the lamps, possibly voiding insurance coverage for damages caused by such product. Three basic sources for lamps were identified, convenience- and department stores and supermarkets, domestic web-shops and low-end sources from international web-shop, namely Ebay. The lamps purchased from supermarkets, convenience stores and hardware stores were divided into two testing groups based on time of purchase. The lamps from domestic web-shops were placed in a third testing group. These three groups occupied a solid portion of the testing rack that was available, thus limiting testing of further models. The test set-up is described in further detail in chapter 5.

Lamps from Ebay took longer to arrive and were thus tested separately as a single test group. However, initial testing revealed the Ebay lamps from China to be a major disappointment. Due to suspected lack of or even fraudulent product information, four lamp models were initially purchased. Of these four groups two were returned to seller due to extremely poor quality. The same almost came to pass for all of these lamps, but the supervisor requested taking them to the test none the less. However, since the lamps didn't meet even the most basic performance and safety requirements, their ageing test was finished prematurely. About two months into the testing some lamps had already failed and the lumen output of all the remaining lamps was rapidly declining. A decision was thus made to make space in the testing rack and stop the ageing test for this group of lamps.

After the initial test groups were selected, the market survey continued, and as a result, another model was added to the ageing test during October. This lamp from V-light had an efficacy exceeding 100 lm/W according to package markings, a claim which seemed interesting to investigate in detail. As the testing rack had been vacated of the sub-par Ebay lamps, the new LED lamp as well as several entry-level CFL were purchased and put to the test. It was obvious from the beginning that these lamps would not reach the required 6000-hour mark during the time that was available for the measurements. Nevertheless, a decision was made to go forward with the purchase and testing, since the CFL were needed for overall performance reference and goniophotometric measurements presented in chapter 5.

Table 8 presents basic LED lamp properties along with the information available from the package markings. This data will be compared to measured data later in the thesis. The lamps purchased from abroad are not included due to lack of packages and markings thereof. The new lamps purchased in autumn 2013 are presented separately at the bottom of the table. Figure 14 shows a line-up of the lamps tested in the thesis.

Table 8: Lamp properties from package labels

Lamp model	Given series name	Power	Average Purchase price (€)	Luminous flux [lm]	Energy class	Rated life [h]	Correlated Colour Temperature	CRI Ra	Dimmable (yes/no)
Airam mini H	H	12W	27.95	810	A	25000	2700K	80	no
Airam miniLED	A	12W	24.95	806	A	25000	2700K	80	no
Biltema LED lamp	B	11W	18.90	800	A	30000	2700K	-	no
Electrogear LED lamp	E	10W	15.90	810	A	30000	3000K	80	no
Osram LED star classic A	O	10W	29.50	810	A	15000	2700K	80	no
Osram LED superstar classic A	Q	12W	48.90	810	A	30000	2700K	80	yes
Philips LED lightbulb	P	10,5W	26.95	806	A	10000	2700K	80	No
Philips Master LED	M	12W	38.71	806	A	25000	2700K	80	Yes 10-100%
Verbatim LED	V	10,0W	29.50	820	A	30000	3000K	80	No
ViriBright LED	D	10W	17.90	820	A	25000	2800K	80	yes
V-light LED	C	11,5W	21.50	810	A	25000	2700K	85	yes
V-light LED (new)	N	8W	17.90	810	A+	25000	2700K	90	no
Airam Longlife (CFL)	I	15W	10	800	A	10000	3000K	80	no
Airam Oiva (CFL)	J	14W	4.50	800	A	8000	3000K	80	no
Airam Spiraali (CFL)	K	14W	8.90	900	A	10000	3000K	80	no
Osram Dulux superstar classic A (CFL)	L	14W	9.95	740	A	10000	2500K	80	no

Figure 14: The tested LED lamps in the same order as in table 8.

4.3.1 Airam MiniLED and MiniH

Imported by Finnish company Airam and manufactured in Hong Kong, China by Neonlite Electronic & Lighting (HK) Ltd. These two lamps are rather generic, consisting of the basic E27 screw with lamp body and heatsink attached.

Due to a number of external similarities, it was assumed these two lamps shared the same technology. The heat-sinks were different, however, the H version having a more traditional finned heat-sink while the MiniLED version had only a plain, roughened external surface made of aluminium. The LED modules and drivers turned out to be completely different. Both of the lamps were selected, so that the difference in the cooling performance could be studied. Lamp properties from packages are presented in table 8.

4.3.2 Biltema LED lamp

This lamp was selected for two primary reasons. First of all, distributed by Biltema Ltd, it was available throughout Nordic countries as well as northern Europe. Secondly, it was sold at relatively low price compared to most of the other lamps tested. Biltema, at least in Finland, has a reputation of selling items lacking in quality cheaply. Thus testing this lamp was deemed interesting. The first impression, however, was rather positive: The lamp had a very unique design and seemed to perform rather well. Unlike most of the tested lamps with hemispherical dome, this lamp supposedly had much wider distribution of light. Figure 15 presents the lamp from several angles in order to demonstrate the structure.

Figure 15: The distinct three-lobe structure of the Biltema LED lamp from several angles.

4.3.3 ElectroGear LED

Imported by Kauppahuone Harju OY (Ltd) and distributed by Puuilo OY, a hardware store importing many products from Asia, the ElectroGear lamp was the cheapest domestically sold lamp at the time of selection. It was, therefore, interesting to see, how well it would perform in contrast to other, more expensive baseline models. The design of the lamp was fairly orthodox, employing a cast aluminium heat-sink and plastic hemisphere dome. Notably, this lamp was withdrawn from the market in late 2013 due to electrical safety concerns [75].

4.3.4 Osram LED star classic A60

This rather new model from Osram was selected mostly due to its supposedly recent technology. The basic design was very similar to the Airam MiniLED as they both shared the simple smooth aluminium surface heat-sink that was shaped like a light-bulb. The lamp had a hemispherical plastic dome and a painted, smooth metallic body. Overall, a rather ordinary design.

4.3.5 Osram LED superstar classic A60

A high-end product from Osram, this model was dimmable by incandescent dimmers. It was selected as a high-end lamp from Osram in contrast to the entry-level LED star classic. It was unarguably the most expensive lamp in the test group, and thus high expectations were held on its performance. The design of the lamp was relatively standard, consisting of E27 screw base, painted aluminium heat-sink and a flat plastic dome. It was also noted that the superstar was easily the heaviest lamp of the whole test group at 232 grams.

4.3.6 Philips LED lightbulb

Having similar, small form-factor to a traditional light-bulb, the entry-level model from Philips was probably the most widely available lamp domestically. It was selected for solely this reason, while it could also be compared to the more expensive Master LED lamp. The structure of the lamp was similar to most of the tested

LED lamps, with the exception that the lamp body was manufactured from thermally conductive plastic, judged by its slight translucency. This design solution was probably done to reduce manufacturing and material costs of the lamp as well as to simplify its structure. If any savings were made, it could not be seen from the vendor price, however, being higher than average for entry-level lamps in all sources. Thermal performance of this lamp would thus be extremely interesting to study and measure.

4.3.7 Philips Master LED

Purchased through a domestic web-shop and also occasionally found on convenience stores, the Master LED utilises the remote phosphor technology where the phosphor material is not encapsulated within the LED components but a separate optical component. The design of this lamp was certainly unique, following the Philips L-price lamp quite closely [73]. The design has three remote-phosphor lobes with six blue LEDs beneath each lobe. As the lighting unit already had one of these lamps purchased roughly two years prior this thesis, it was possible to deduce that the technology had received several updates during it's time on the market. The new version consumed less power, but also gave out less light as can be seen in luminous flux measurements presented in chapter 5.2. This model could also be considered as the high-end from Philips as the lamp was both dim-able and relatively expensive. figure 16 displays the distinct

Figure 16: The Philips Master LED with its remote phosphor lobes visible.

4.3.8 Verbatim LED lamp

A generic LED lamp from a manufacturer more famous of their data storage devices, the Verbatim lamp was on the expensive side of the entry-level lamps. Its selection was due to request of thesis supervisor. The build of the lamp was very solid, incorporating the E27 base, finned aluminium heat-sink and plastic hemisphere dome. The colour temperature of this lamp was higher than most of the test group, probably an attempt at increasing efficiency. Over all, it seemed like a generic, well-performing, albeit rather costly lamp.

4.3.9 ViriBright LED lamp

ViriBright was the other web-shop lamp purchased for testing. Manufactured and designed by a Chinese company of the same name, it is arguably very innovative design, boasting rather extensive patent portfolio. However, the lamp itself was relatively low-cost, dim-able and omni-directional. The technology was also based on remote phosphor, but interestingly, the red end of the spectrum was produced by monochromatic red LEDs, avoiding some of the losses due to Stokes' shift. While the efficiency could be made higher than with pure phosphor conversion, the colour stability might be an issue. As one failed lamp was studied in more detail, it was indeed confirmed that the blue and red LED sources were wired in series, eliminating any possibility of feedback and control over the lamp colour. The lamp also consisted of a large number of separate parts, mostly assembled by hand, judging by the finishing quality and methods of assembly. Due to the relatively low price and large number of manual assembly phases, this lamp was somewhat a dilemma, as it was hard to see how the vendor price could be met without outrageously cheap labour.

4.3.10 V-light LED lamps

The V-light was imported and sold by Clas Ohlson department store chain, distributing these lamps throughout the Nordic countries. It was selected to the test as cheap, dim-able lamp also utilising an interesting combination of greenish-white and red LEDs to produce white light. This was verified in the store with Konica Minolta CL-500A portable illuminance spectrophotometer. As discussed in chapter 3.3, this technology would typically require some form of feedback to retain colour stability of the lamp in different operating temperatures throughout the lifetime. Considering the price of the lamp this seemed unlikely, and it was thus interesting to test the lamp for possible variation throughout the ageing test.

During October 2013, a new model was released and sold at Clas Ohlson. The package markings claimed efficacy exceeding 100 lm/W and thus, a batch of these lamps was purchased for study. The new lamp had curiously small, ceramic heat-sink and spherical glass dome.

5 Methods

This chapter describes the methods used in measurements and testing set-ups. It also introduces and justifies the use of TM-21 methodology to estimate the ageing behaviour of the tested lamps.

5.1 Photometric and electrical parameters

In order to estimate the photometric and electrical performance of the tested lamps, they were measured in the facilities of Aalto University Lighting Unit. The measurement was conducted for all the lamps at least once, and for the ageing test series, several times throughout the duration of the test.

Measurement set-up for luminous flux consisted of Labshpere diode array spectrometer with 2-metre integrating sphere and a laptop PC with respective software for running the system. The set-up, in addition to luminous flux, could also be used to measure radiometric power, spectral power distribution (SPD) and colour parameters, such as colour co-ordinates and correlated colour temperature (CCT) of the tested light source. A Yokogawa WT13 digital power meter could also be used to measure power factor and phase angle. The laboratory room was temperature controlled, but for the duration of the testing, this control was not functional. Thus, the temperature in the room varied between 22 and 24 degrees centigrade instead of $25\,^{\circ}\mathrm{C} \pm 2\,^{\circ}\mathrm{C}$ as was specified by standards [11].

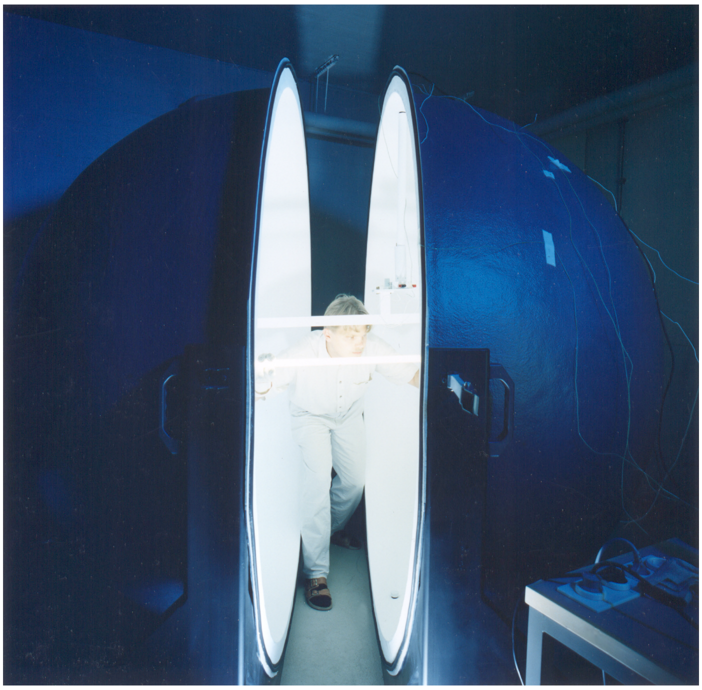

Figure 17: The 2-metre integrating sphere of Aalto Lighting Unit.

To facilitate testing procedure as well as to minimise time used for manual labour, the lamps were arranged in four groups based on availability. The first four lamp types that were purchased were placed in group number 1 and the second four in group 2. Lamps purchased from domestic web-shops were placed in group 3 due to longer time of arrival, and for similar reason, lamps from abroad web-shops were placed in group 4. Table 9 presents the arrangement of lamps within the groups.

Table 9: Test groups of lamps. The series identifier letters were chosen from lamp trade names or vendors initials.

Group 1 lamps (Convenience store 1)	**Group 2 lamps** (Convenience store 2)	**Group 3 lamps** (Domestic web-shops)	**Group 4 lamps** Fall 2013
Philips LED lighbulb 10W (series P, 5 lamps)	Airam MiniH LED A60 (series H, 5 lamps)	ElectroGear LED (series E, 5 lamps)	V-light LED lamp 8W (Series N, 5 lamps)
Osram LED star A60 (series Q, 5 lamps)	Osram LED superstar (series Q, 5 lamps)	Philips Master LED bulb (series M, 5 lamps)	Airam Oiva 14W (CFL, Series J, 3 lamps)
Airam MiniLED A60 (series A, 5 lamps)	V-light LED (series C, 5 lamps)	Philips MyAmbiance LED (series M, 1 lamp)	Airam longlife 15W (CFL, Series I, 3 lamps)
Biltema LED lamp A60 (series B, 5 lamps)	Verbatim LED Classic A (series V, 5 lamps)	ViriBright LED light bulb (series D, 5 lamps)	Airam spiral 14W (CFL, Series K, 3 lamps)
			Osram Dulux classic A 14W (CFL, Series L, 3 lamps
In total 20 lamps	**In total 20 lamps**	**In total 16 lamps**	**In Total 17 lamps**

Outside measurements, the lamps were kept in a rack of 80 lamps, socket upwards. During measurement process, ten lamps at a time were removed from the rack, placed to a moveable rack and taken to the integrating sphere laboratory. There, the lamps were allowed to stabilize for one full hour in socket-upwards position, as per common practice, in the same laboratory space as the instruments. In the meanwhile, auxiliary lamp calibration was conducted on the equipment, using a single model of a single series of the test group as a reference. Table 10 presents the lamps used in auxiliary lamp calibration as nominal lamp.

Table 10: Nominal lamps for auxiliary lamp calibration per group.

Lamps:	Group 1	Group 2	Group 3	Group 4 N	Group 4 I & L	Group 4 J 6 K
Reference	P	H	E	N	L	K

This was to ensure the integrating sphere was properly calibrated for the lamps and socket used, as there were other users to the system during the measurement phase of the thesis. Using the same reference lamp each time minimised calibration error. After the one-hour stabilisation period, each lamp in turn was placed into the integrating sphere and stabilised for further 5 to 15 minutes, depending on what was observed as sufficient. Most of the LED lamps seemed to stabilise during initial 5-10 minutes, but the CFLs tested required up to 30 minutes to become fully stabilised. As mentioned, central photometric and electrical parameters were recorded by the set-up. Recorded parameters include Luminous flux, Correlated colour temperature, radiative power, CIE 1931 xy colour coordinates, CRI Ra, electrical input power, electric voltage and current and power factor. After the initial measurement, the ageing test was started for groups 1 through 3. Group 4 was acquired later and was not put to the ageing test. The initial values were recorded shortly after purchase. As written in the lighting standards, no burn-in period was required for the LED lamps [11].

5.2 LED lamp ageing - TM-21-11 methodology

As LED technology is still in a process of making a breakthrough to the lighting market, so are the methodologies used to estimate LED performance, especially in long term. It was thus somewhat a daunting task to try and find a methodology suitable for rating the tested lamps and estimating their potential lifetime. Simply testing the lumen depreciation until the lamps reach their L70-value was simply impractical as this could technically take as long as several years of continuous monitoring. Accelerated ageing methods were found insufficient for the number of lamps to be tested and there was also another issue. There was no reliable temperature control possibility in the laboratory room where the ageing test took place and thus, a controlled accelerated test could not be conducted.

As described in chapter 5.1 lamps were arranged in series by lamp model. A movable rack for ten lamps was constructed to facilitate moving of the lamps from the testing room to integrating sphere laboratory. In the ageing test, all lamps were placed in rows of ten on a rack that could hold 80 lamps in total. The lamps were positioned socket upwards in calm air. As the lamps were organised into three (later four) groups, each group was wired separately with an hour counter attached. This was done to ensure a correct burn-time could be recorded even in the case of power outage. All the lamp groups were supplied through mains voltage stabiliser transformer and the mains voltage was checked periodically. The initial temperature in the room was 23 °C, but quickly rose to 30 ± 2 °C as the lamps were turned on. There was no way to control the temperature inside the rather poorly ventilated space and thus a thermometer was set up to record the temperature. Fortunately, after the initial warm-up, the temperature remained relatively stable around 30 °C.

The duration of the ageing test was chosen as 6000 hours [11] [13]. The measurement intervals were shortened to 500 hours due to recommendation in the extrapolation methodology [17]. In addition to simply measuring the decrease in luminous flux periodically during the 6000-hour test, an attempt was made to estimate the future behaviour of the lamps based on the TM-21-11 methodology. The TM-21 is itself relatively new, but has already been widely accepted in the lighting industry. It does, however, have some limitations that are discussed here. The TM-21 is aimed at estimating lumen depreciations from data measured according to approved method IES LM80-08 [13]. This methodology describes measurements on LED chips, components and modules, but not full LED products. Similarly, approved method LM79-08 covers LED luminaires, but does not have an attached extrapolation method.

Another limitation of TM-21 is the required sample size. The TM-21 recommends a minimum sample size of 10 LEDs. In this case, the maximum recommended extrapolation time is 5.5 times the real data. Thus, for 6000-hour test period, a valid extrapolation time would be 33000 hours. If 20 samples or more were to be used, the estimation time could be increased to 6 times the actual data [17]. The method also mentions that having the sample size larger than 20 does not significantly increase accuracy of the prediction. In the test conducted by this thesis, only 5 lamps per model were available for testing. Although this is lower than the minimum sample size recommended by TM-21, it could be argued that an LED lamp already consists of dozens of LED chips, which are averaged at the time of measurement automatically.

In the heart of the TM-21 lies an extrapolation method for acquired luminous flux data. The methodology describes the selection of data points, calculation of factors of an estimating exponent function and finally extrapolation of the data. First and foremost, all the samples from the test series are averaged together, thus forming a single time-luminous flux pair. The data is then normalised to the average initial luminous flux of the series. The methodology states that for estimations in excess of 10000 hours, last 50% of the data points should be used for the extrapolation. In the case of the ageing test of this thesis, this meant using data points measured after 3000-hour mark. The estimating function is a simple exponential representation described in equation 2.

$$\Phi(t) = \beta \cdot e,^{-\alpha t} \tag{2}$$

Factors α and β are calculated from a linear fit of the selected data using least squares method. The resulting extrapolation function is a normalised, averaged luminous flux at time t. Limitations include minimum t of 6000 hours and extrapolation up to 33000 hours. For calculating L70-values from the extrapolated data, equation 2 can be used as follows:

$$L_{70} = \frac{1}{\alpha} \cdot ln(\frac{\beta}{0.7}) \tag{3}$$

However, it has to be taken into account that L70-values above 33000 hours are not valid in the case of this ageing test and have to be truncated into 33000 hours. However, different L70-values of the lamp models could be compared and analysed further. A possibility for a follow-up study has been proposed, where, the lamps would continue to be monitored well beyond 6000 hours. In this case the follow-up study could validate calculated L70-values and the extrapolation as a whole.

5.3 Angular light distribution - goniophotometer

In order to find the angular light distribution of the tested lamps, Lighting units new goniometer was used. The equipment itself consists of an OxyTech heavy duty rotating beam goniometer with moving Gamma and C-axes, A Czibula& Grundmann point luxmeter placed 4.59 meters from the pivot point and OxyTech SRL Gonio control PC software to control it. Auxiliaries include Elettrotest test power supply TPS/M and N4A PPA1530 power analyser, also connected to the PC. A special lamp holder had to be machined for the goniometer to accommodate the E27 lamps being tested.

A 5G15C measurement scheme was used, which means a data point was taken each 5° of gamma angle (azimuth) for full 360° and then C-plane was rotated 15° and gamma measurement repeated. In this way, a 3-dimensional light distribution data file was achieved. For the purposes of this thesis, exports of C0 and C90 planes were considered sufficient.

6 Results and analysis

This chapter presents the results of various tests described in chapter 5. Greatest emphasis is put upon lamp ageing, failures and derivative results. Goniometric measurements, conducted during the testing phase, are only reviewed briefly. However, some important conclusions are drawn from the luminous intensity distribution data as well.

6.1 Lamp performance

The overall performance of the lamps was measured under testing conditions and using the integrating sphere and equipment described in chapter 5.1. In addition to the lamps in ageing test groups, several other lamp types were measured. These were mostly recently launched LED products to keep the information up to date. As already discussed, LED technology improves rapidly and timely performance data is thus hard to obtain. Several models of modern CFL were also included in the initial testing as reference to LED lamp performance. All lamps were measured in test series before the start of the ageing test, thus, the values reported are initial. The CFL were aged 100 hours before measurements as per corresponding measurement standard [30]. The LED lamps required no initial ageing period. Table 11 presents photometric and electrical performance figures of the lamps. As the lamps were measured by model in series of 5, these results are an average of the whole test series. In the 'technology' column, 2PC refers to dual phosphor-converted white LED and PC+R refers to PCWLED+R with greenish white and red LED.

Table 11: Photometric and electric performance of tested lamps.

Lamp	Code	Tecnology	Luminous flux [lm]	Measured power [W]	Power factor	CCT	CRI Ra	Luminous Efficacy [lm/W]	Conforms to EC 244 in stage 5	Conforms to Energy Star
Airam Mini LED	A	LED 2PC	749	9.78	0.58	2845	83	76.6	YES	No application icons
Biltema LED x3	B	LED 2PC	865	11.66	0.96	2730	85	74.2	YES	No application icons
Osram LED star	O	LED 2PC	877	11.46	0.94	2720	84	76.5	YES	No application icons
Philips LED lightbulb	P	LED 2PC	825	9.80	0.59	2743	83	84.2	YES	No application icons
Airam miniH	H	LED 2PC	739	10.44	0.48	2764	82	70.8	PF too low < 0.55!	PF too low < 0.5!
V-light LED lamp	C	LED PC+R	834	11.10	0.66	3334	81	75.2	Too much variance CRI, CCT	
Osram LED superstar	Q	LED 2PC	772	12.30	0.96	2761	83	62.7	Directional by def.	No application icons
Verbatim LED lamp	V	LED 2PC	864	9.96	0.93	2950	85	86.7	YES	No application icons
Philips Master LED	M	LED R2PC	867	10.80	0.77	2646	82	80.3	YES	YES
ElectroGear LED	E	LED 2PC	828	9.44	0.77	3034	85	87.7	YES	No application icons
ViriBright LED lamp	D	LED PC+R	810	9.60	0.94	3109	83	84.3	YES	No application icons
V-light LED lamp 8W	N	LED PC+R	774	7.43	0.53	2837	89	104.1	PF too low < 0.55!	No application icons
Airam Oiva 14W	J	CFL A	812	13.93	0.59	2969	85	58.3	YES	No application icons
Airam Longlife 15W	I	CFL A	973	15.40	0.61	3098	84	63.2	YES	No application icons
Airam Spiraali 14W	K	CFL A	862	15.33	0.60	3041	84	56.2	YES	No application icons
Osram dulux 14W	L	CFL A	740	13.53	0.60	2605	83	54.7	YES	No application icons

Whilst most of the tested lamps met the initial performance requirements of the EC regulation 244 presented in chapter 2.1, Most failed to meet Energy Star requirements. The non-standard distribution of luminous intensity would, according to Energy Star specifications, require the usage of application icons presented in chapter 2.1.4. As the Energy Star is not utilised inside EU, these were naturally not used on lamp packages. Issues with non-standard distribution of light will be discussed further in chapter 6.5.

Most of the lamps had CCT values centred around 2700 K, akin to that of the incandescent lamp the retrofits were designed to replace. Some models, however, had purposefully higher CCT of around 3000 K. This was undoubtedly done to increase the luminous efficacy through reduced need for red emission in the spectrum. While there certainly is a difference on paper, the dissimilarity would probably only be observed through comparison. It is thus unlikely the consumer would notice any meaningful difference unless comparing two lamps with different CCTs side-by-side. Furthermore, some studies and articles indicate higher colour temperatures are actually preferred over more traditional, incandescent-like yellowish whites.

Concerning LEDs, luminous efficacy typically takes the spotlight. Luminous efficacy of the lamps was calculated from measurement data. Figure 18 presents recent efficacy results as well as older ones for reference. Additionally, formula 1 from chapter 2.1.3 was used to plot the limits of the energy classes.

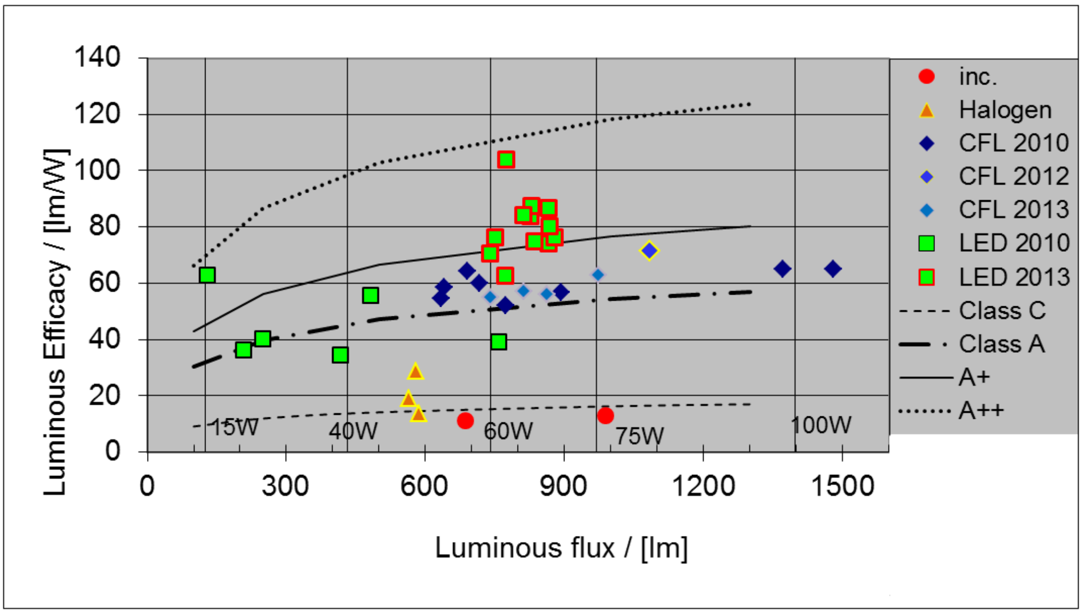

Figure 18: Efficacies of tested lamp groups from Aalto University studies [4].

The figure also brings a glimpse into the near history of the LED retrofits. As can be seen, in 2010 LED lamps were available, but the efficacies were still insufficient by today's standards. LED lamps to replace 60 W incandescent also weren't as readily available as today. As announced earlier, all the lamps tested by this thesis were aimed at replacing 60 W incandescent lamp. The modern end of the tested lamps (excluding series Q and H) all reside in energy class A+, clearly distinct from CFL that can seemingly only reach class A. An interesting contrast can be seen between results from Aalto University studies and those of CALiPER, presented in chapter 4.1. It also shows how LED retrofit lamps were much more developed in USA than in Europe in 2011. This development was undoubtedly driven by Energy Star and stricter requirements in general. Fortunately, the development in LED retrofit has been extremely fast in the last few years, even in Europe. The modern LED lamps clearly triumph over CFL in pure luminous efficacy.

6.2 Ageing test results

In order to estimate usage costs of LED lamps, some figures for the lifetime of these lamps is required. To that end, this thesis conducted an ageing test for 6000 hours recommended in most reviewed standards. After the ageing test, the data was extrapolated with TM-21 methodology introduced in chapter 5.3.2 for L70 estimation.

6.2.1 Lamp failures

Whilst most of the lamps performed admirably and continue to perform even at the time of writing, a number of lamps failed completely due to multitude of reasons. In the interest of finding out the cause of failure, a post mortem was performed and the faulty component narrowed down. Table 12 presents complete failures by lamp model and specifies cause of failure.

Table 12: Failed lamps by model.

<table>
<tr><th>Lamp Series</th><th>Code</th><th>Failures</th><th colspan="6">Cause of failure</th></tr>
<tr><td>Osram LED star</td><td>O2</td><td>1</td><td colspan="6">4391h, driver failure</td></tr>
<tr><td>V-light LED lamp</td><td>C3 & C6</td><td>2</td><td colspan="3">7800h, driver failure</td><td colspan="3">6380h, driver smoked out</td></tr>
<tr><td>ElectroGear LED</td><td>E5</td><td>1</td><td colspan="6">2660h, mechanical failure of socket while handling</td></tr>
<tr><td>ViriBright LED lamp</td><td>D2, D3 & D4</td><td>3</td><td colspan="2">692h, half of LEDs</td><td colspan="2">45-110h, half of LEDs</td><td colspan="2">4989h, driver</td></tr>
</table>

While three lamps of series D (ViriBright) suffered a failure of some extent, it has to be noted that the luminous flux of these lamps was already declining fast and the rest of the series reached their L70-values in little over 3000 hours. It can be thus considered the worst of the tested lamp models, failing to live up to lifetime claims and reliability. Notably, this particular lamp model consisted of a myriad of separate parts and was by far the most complex one structurally. Furthermore, whilst taking a specimen apart for detailed failure analysis, it quickly became obvious this lamp could only have been assembled using considerable manual labour.

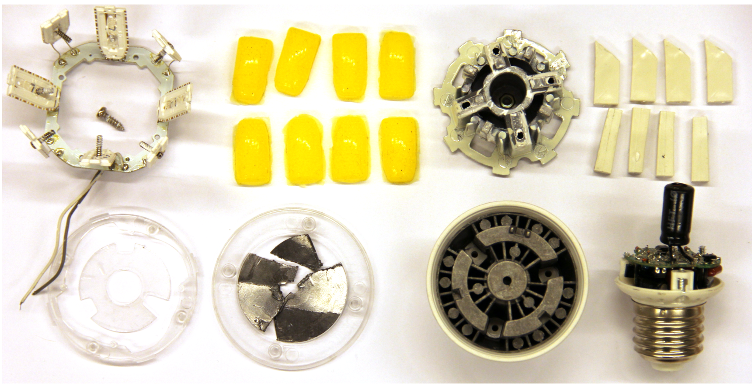

Figure 19: Dismantled ViriBright LED lamp, displaying a myriad of parts.

The failure of the single lamp in series E was most probably due to a manufacturing defect since the lamp had had rather wobbly base from the beginning. The base came off after multiple successive changes of socket, something a lamp would probably not have witnessed had it been used in a household as intended. It is thus entirely possible this single specimen would have performed to norm and is thus not counted as a real failure per se. Manufacturing defects such as these are unfortunately common in low-end lamps and it seems even this model fell victim to parsimonious design and manufacturing practices. A sales ban was imposed to the model by TUKES in November 2013 due to risk of electric shock [75].

The remainder of the failed lamps were of more traditional construction, and the drivers accounted for the remnant of the failures. Two drivers in series C failed, one quietly and one catastrophically, spewing black soot-like dust into the LED compartment, blackening the dome from inside. For series O, the driver failure was uneventful and was noticed after the lamp had cooled down already. In all occurrences, the post mortem simply revealed the driver was no longer providing power to the LED module although it was receiving mains voltage through the socket. The LED modules themselves worked when driven through a laboratory power supply. The failed drivers, on the other hand, could not be investigated further to determine the exact point of failure.

6.2.2 Lumen depreciation

As described in chapter 5.3, the lamps were monitored throughout the duration of the ageing test by measuring them with the integrating sphere in series by model. The recorded parameters encompassed both photometric and electrical performance figures in order to track any ageing-related developments. Thus, additionally to luminous flux depreciation, the data gathered could reveal possible driver failures and malfunctioning as well as colour coordinate and -temperature shifting. The testing period spanned the recommended 6000 hours and lasted more than 8 months in actual time. Testing itself also required considerable amount of time and manual effort to accomplish, since no automated system to measure individual lamps was in place. The luminous flux of each lamp was recorded at approximately 500-hour intervals and the fluxes of a lamp model were averaged. Figures 20 through 22 present averaged luminous flux of the lamp test series as function of testing time.

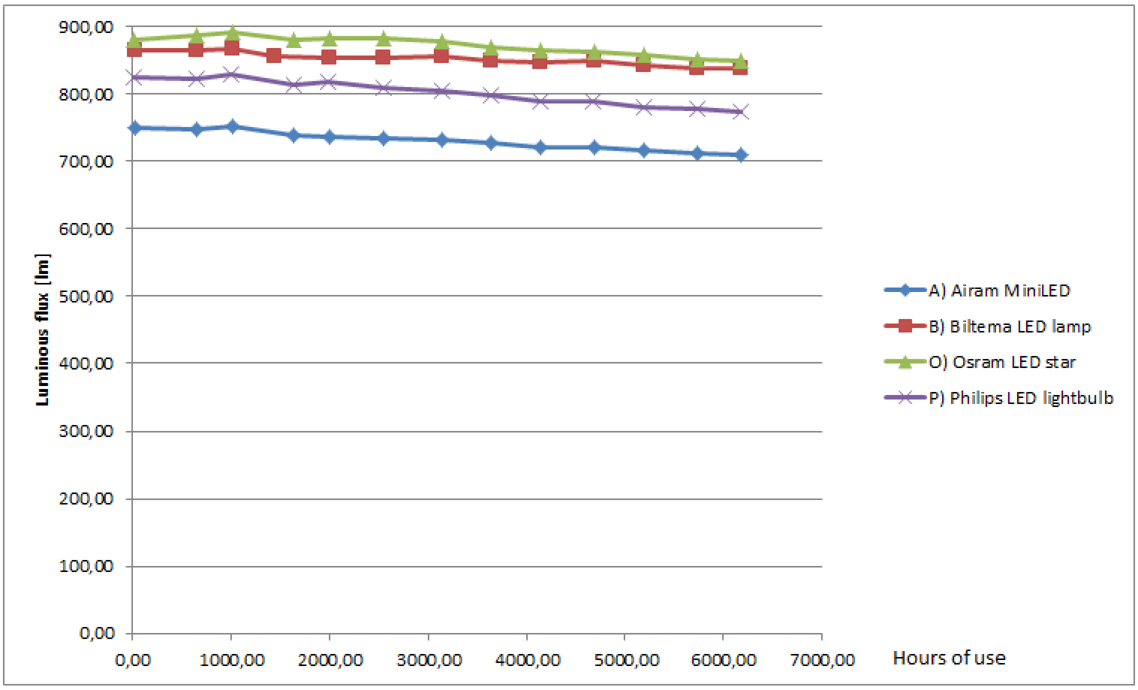

Figure 20: Lumen maintenance of test group 1.

The first test group (series A, B, O, P) was relatively uniform and the decrease in absolute luminous flux remained under 5% in all models. Some ripple was detected in the first half of the measurements, but the depreciation speed of the luminous flux settled rather linear eventually.

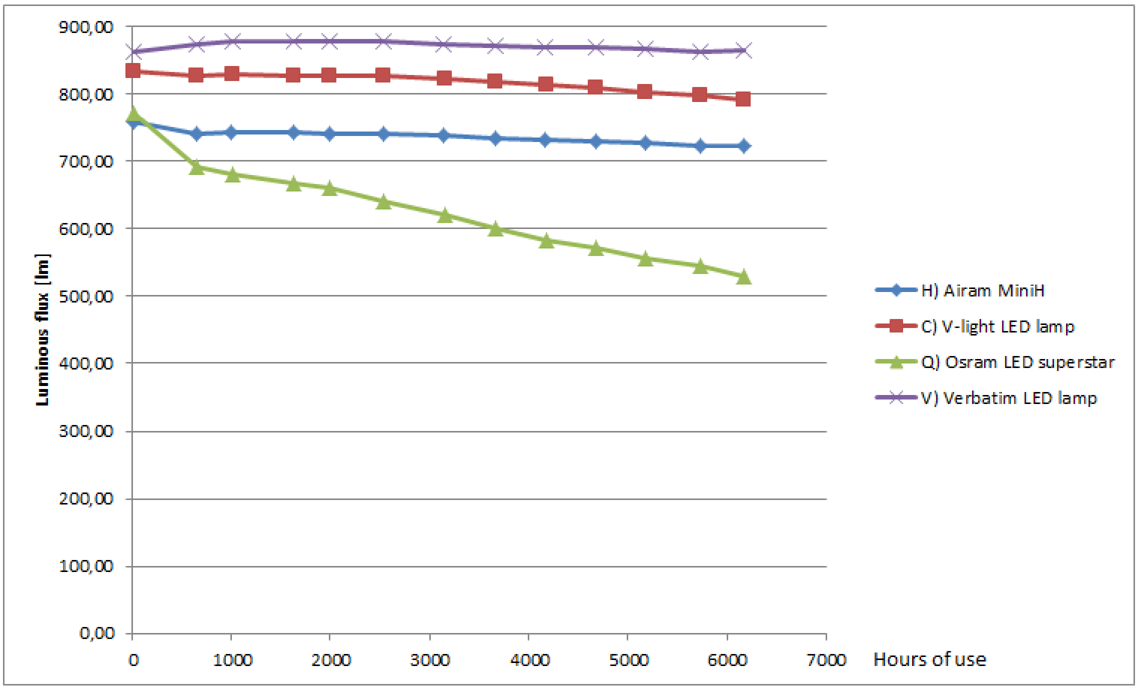

Figure 21: Lumen maintenance of test group 2.

Group 2 included series H, C, Q and V, and performed more or less similarly than group 1, except for series Q. Interestingly, this lamp, manufactured by Osram, was the most expensive lamp tested. It was also marketed as premium product, as implied by the 'superstar' name. A dimmable, compact lamp with good power factor, it initially performed no worse than other lamps. However, a few thousand hours into the test it became obvious these lamps were degrading fast. The lamps in series Q eventually reached their average L70-value at 5804 hours, interpolated from data. As random sampling was employed in purchasing of the lamps, the observed effect can hardly be a problem with a small sales lot, but probably concerns a whole bulk lot imported sometime in spring 2013.

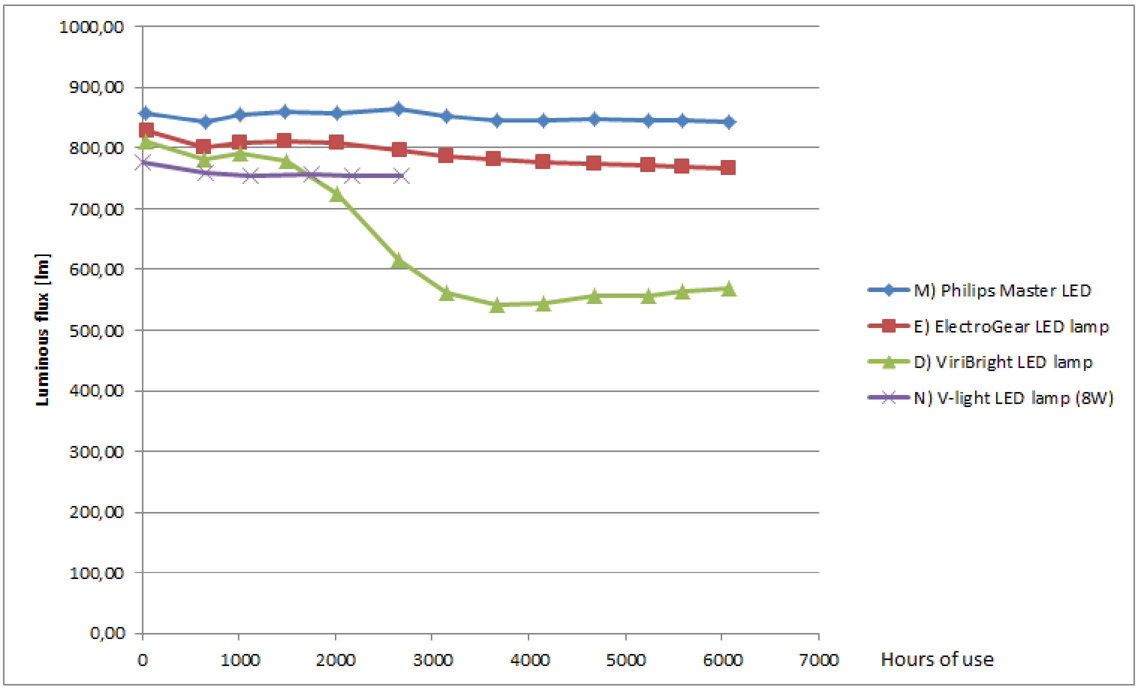

Figure 22: Lumen maintenance of test group 3.

Group 3, comprised of series M, E, D and additionally N, was interesting in that it contained one high end lamp from Philips, the cheapest lamp of the test from ElectroGear and the now-infamous ViriBright. As already mentioned in chapter 6.2.1, half of the lamps in series D died completely during testing. This, compounded with the fact that the series reached its L70-vale in mere 3103 hours (interpolated from data) made it the worst lamp tested by far. An interesting design, an engineering problem to steer clear of and a nightmare to assemble, it is inconceivable how this lamp could be sold with such a low retail price. As mentioned in 6.2.1, buying this lamp is not recommended by this thesis.

Series N was introduced much later and wasn't in the full 6000-hour ageing test. However, results thus far seem promising as the degradation of luminous flux has already settled. It would have been interesting to follow the ageing of this multi-chip LED lamp

The data presented in figures 20,21 and 22 clearly show decreasing lumen output on all the tested lamps. Whilst it can be seen that the luminous flux of many lamps fluctuated considerably during the first half of the testing period, the depreciation eventually settled to more linear behaviour. Similar behaviour was observed on all of the tested lamps, persevering for 3000 hours in most cases. Thus, extending the ageing test to 6000 hours seems to have been a sound decision, since the relatively linear, calm data didn't occur before 3000 hours for most of the lamps. Chapter 6.3 further discusses this and performs an extrapolation to the data presented here in order to estimate L70-values for the remaining lamp series.

6.2.3 Colour stability

Along with other photometric attributes, the ageing test also included CIE 1931 xy colour coordinates and correlated colour temperature. These parameters were monitored throughout the testing period and the results are presented here. As discussed in chapter 4.3.3, white light can be produced by LEDs in several manners. Whilst multi-phosphor white LEDs are relatively stable, exposing them to elevated temperatures can result into phosphor degradation over time. Multi-chip LEDs fair much worse here; difference in ageing and temperature performance of the different LED chemistries can cause both shifting and severe drifting in colour coordinates. Ultimately the only way to ensure colour stability on multi-chips is active feedback optically or at least thermally. This is, however, expensive and was not used in any of the tested lamps employing multi-chip technology. The shift in correlated colour temperature is visible from figures 23 and 24.

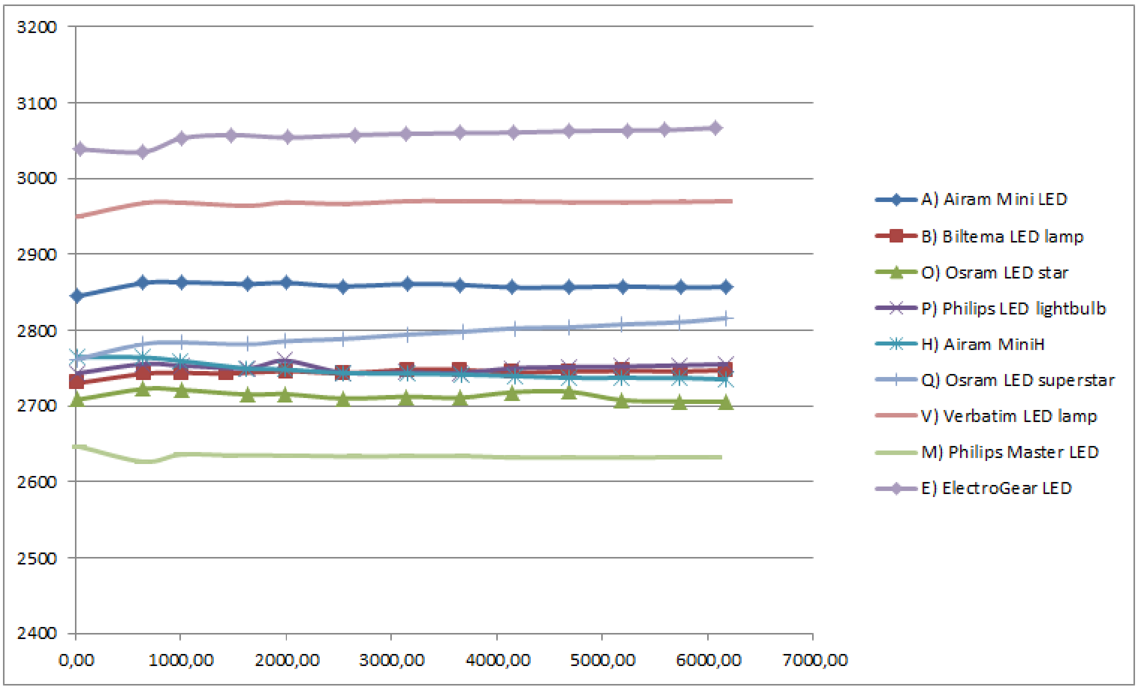

Figure 23: CCTs of phosphor-converted LED lamps over time.

As seen in figure 23, the purely phosphor-converted single-chip LED lamps had relatively little shift in their CCT. All of the lamps seemed to go through an initial 'burn-in' period where some sort of settling occurred. After roughly 1000 hours the CCT settled and experienced little drift with a notable exception of series Q. As discussed previously in chapter 6.2.2, the Q series lost luminous flux rapidly. As the CCT increased simultaneously, it can be hypothesised that at least part of its lumen depreciation can be accounted to phosphor degradation.

Figure 24: CCTs of quasi-multichip LED lamps over time.

The quasi-multichip LED lamps were, in their own way, slightly more interesting. Due to the high internal variance in the tested lamps, the results are presented here per single lamp. Notably, the effect of initial 'burn-in' is much higher than with purely phosphor-converted LED lamps. However, lamps in series C display relatively little shift after the initial 'burn-in', stability being very similar to regular phosphor-converted LEDs. Series D (ViriBright), however, displays a large decrease in colour temperature. The slope somewhat correlates with the decrease of luminous flux presented in figure 22. Notably, for lamp D2, half of the LEDs failed resulting the surviving half being driven at double current. Localised heating can probably explain the fluctuation. As for Series N in 4th test group, the data shows a clear increase in CCT, continuing well into several thousand hours of lifetime. This large a shift is simply unacceptable by Energy Star requirements as seen in table 5 in chapter 2.1.4. It is quite unfortunate to witness such development from a lamp that initially boasted very admirable performance.

Remarkably, after burn-in, the multi-chip LED lamps seem to fair no worse than their phosphor-converted counterparts in terms of colour stability. However, during testing it was discovered that the CCT values of these multi-chips actually fluctuates quite much. Series N, for instance, started from 2500 K cold and drifted to 2800 K when fully warmed up. While the lamp started out way too red (negative Duv), the colour stabilised to a more pleasant hue as the lamp warmed up. Same cannot be said about series C, however. It seems that the designed balance was off the mark and 4 out of 5 lamps attained greenish hue when warm (positive Duv). This particular lamp would not pass the Energy Star colour stability requirements. Overall, the quasi-multichip LED lamps seem to retain remarkable stability over time, but are more sensitive to designed balance and operating temperature. As none of the lamps tested featured any form of feedback, no temperature or ageing corrections can be made to the lamps later on.

In order to investigate possible modes of ageing, the CIE 1931 xy colour coordinates were also recorded throughout the ageing test. As witnessed with CCT, the initial burn-in of the lamps probably resulted in the greatest shift. However, since this thesis was mostly interested in long-term phenomenon, the colour shift after the burn-in was studied further. Figure 25 presents the CIE 1931 colour diagram as a reference. A white light source is supposed to be located on the middle black curve called the Planckian locus. This is the locus of colour coordinates of black-body radiators at different temperatures. A parallel shift to this curve is seen as changing colour temperature and perpendicular shift is seen as hue change between greenish-reddish.

Figure 26 presents the CIE 1931 x-y coordinates of the lamps 600 hours into the ageing test and end of the testing period of 6000 hours. The plots are constructed such that the starting point is in the middle of the chart, showing the direction of the shift intuitively. The absolute scale of the plots is the same in order to preserve the relative scale of the changes.

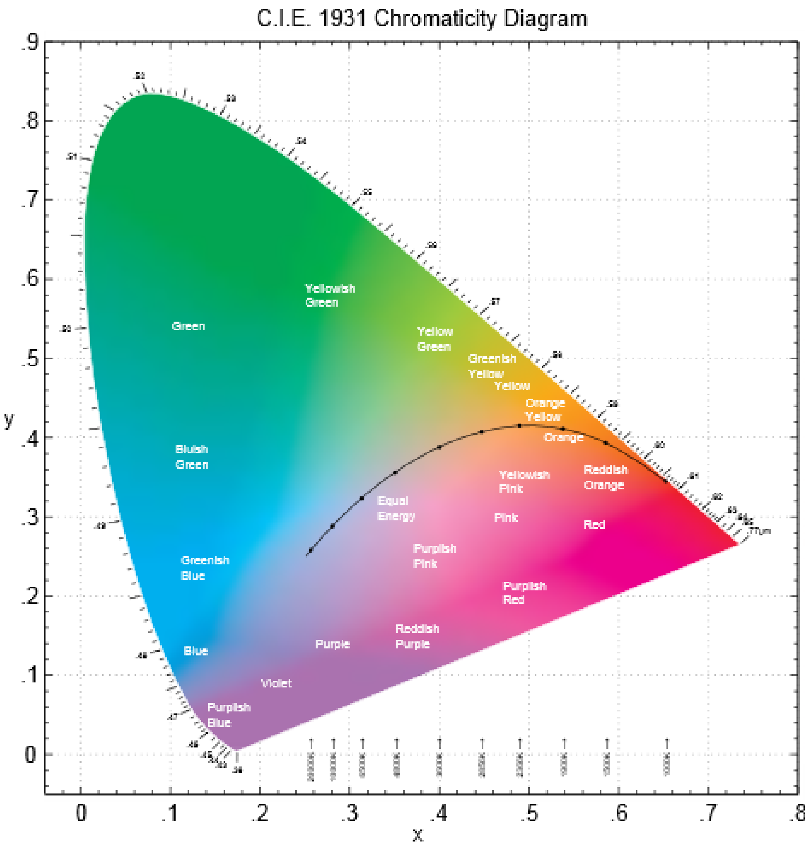

Figure 25: The CIE-1931 colour coordinate system, source: Wikimedia Commons.

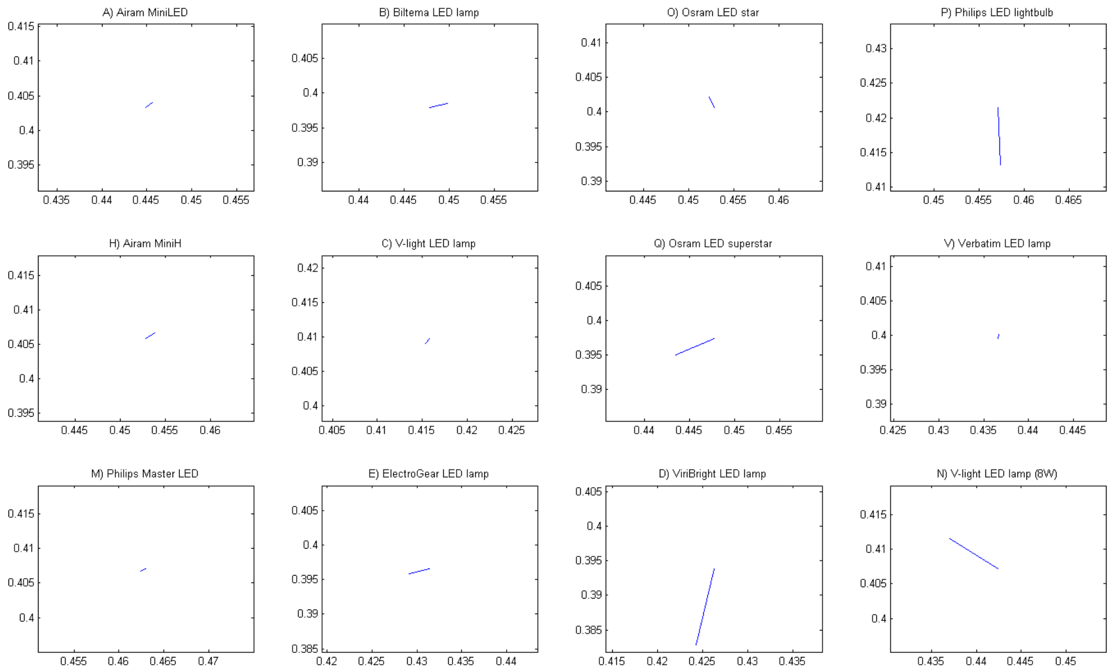

Figure 26: CIE-1931 xy colour shifts of tested lamps.

The multi-chip LED lamps D and N had much more CCT drift than their multi-phosphor counterparts. None of the multi-chip models tested here utilised any form of thermal or optical feedback, as all the LEDs were connected in series. This is by all means the cheap solution, and at the moment doesn't seem to live up to requirements on colour stability. It would be extremely difficult for these lamps to live up to Energy Star chromaticity requirements presented in 2.1.4. The direction of the shift varies between different models, indicating different modes of ageing at play. For instance, colour coordinates of N-series seem shifted towards blue-green, away from red. This might indicate the red LEDs ageing faster than the greenish-white phosphor-converted LEDs inside the lamp. Series D shows a distinct drop in y-coordinate, shifting colour towards the blue-red line of the CIE 1931 Diagram. This suggests the yellow-green phosphor was both degrading and the encapsulation material darkening as the luminous flux decreased simultaneously.

Notable shifts in phosphor-converted LED occurred for series P and Q. Curiously, the colour shift of series Q was affiliated with degrading luminous flux. Furthermore, the direction of the shift from yellow to blue implies phosphor degradation for both the yellow and red phosphors, the combination of which would have colour coordinates in the yellow region. Overall however, the phosphor-converted LED lamps didn't experience much colour coordinate shift and as such fulfil the performance requirements in this regard.

6.3 Lamp lifetime - extrapolation

As shown in chapter 6.2.2, most of the tested lamps reached the end of the 6000-hour test period without their lumen output decreasing too much. However, on the packages these lamps were advertised of having nominal lifetimes of 10000 hours or more. Testing lamps this long would simply be impractical and thus, the 6000-hour data is used to extrapolate and estimate future behaviour of the lamps. The methodology chosen for the test attempted to conform to TM-21, but some allowances had to be made [17]. These include the number of samples of only 5 lamps per model (recommended at least 10 LEDs) and operating temperature of $30\,^{\circ}\mathrm{C} \pm 2\,^{\circ}\mathrm{C}$ instead of $25\,^{\circ}\mathrm{C}$. The former was decreed to limit the labour and consumables cost of the testing. The temperature in the ageing test room could not be efficiently controlled and thus rose quickly to $30\,^{\circ}\mathrm{C}$, where it remained throughout the testing period.

The extrapolation method applied for the data is presented and explained in chapter 5.3.2. As in the description, the luminous flux could only be extrapolated for 5.5 times the actual data due to low number of samples. Figure 27, 28 and 29 present the actual data and the applied extrapolation. The extrapolating functions were also used to calculate an estimate for the L70 values.

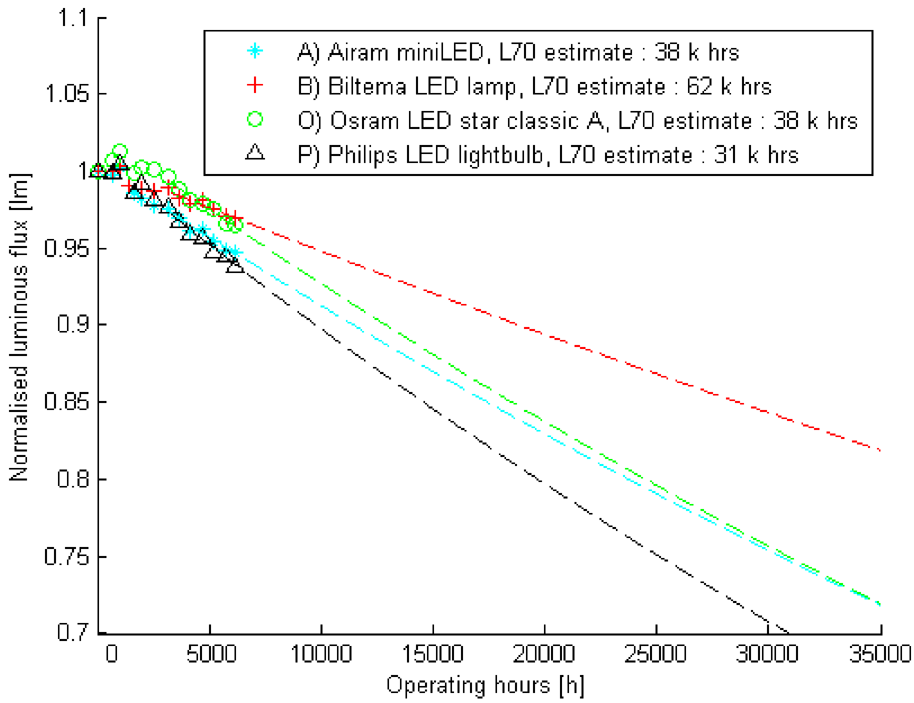

Figure 27: Extrapolated lumen depreciation of group 1.

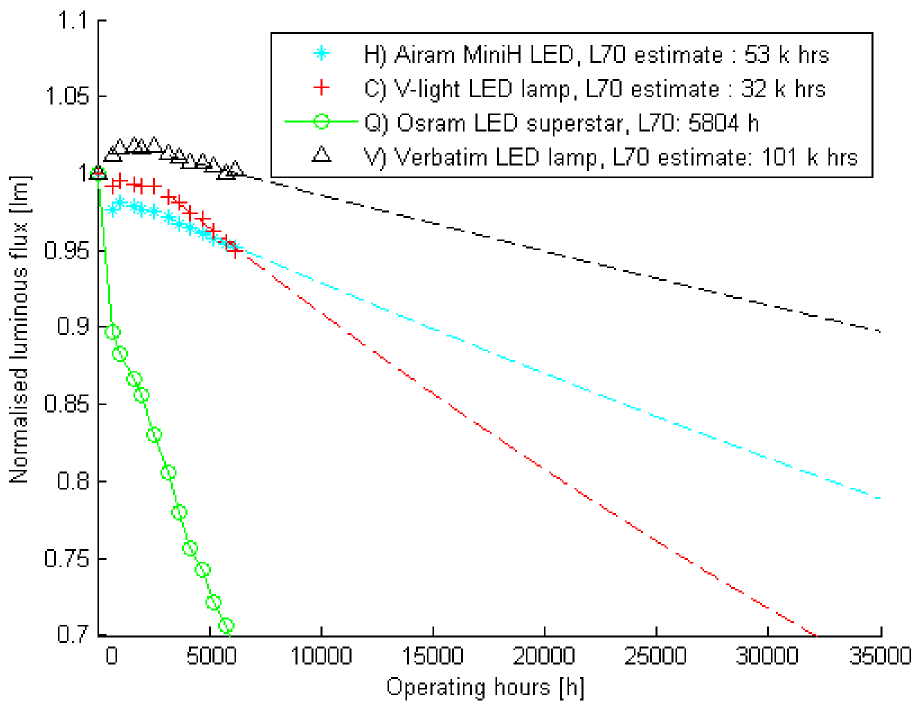

Figure 28: Extrapolated lumen depreciation of group 2.

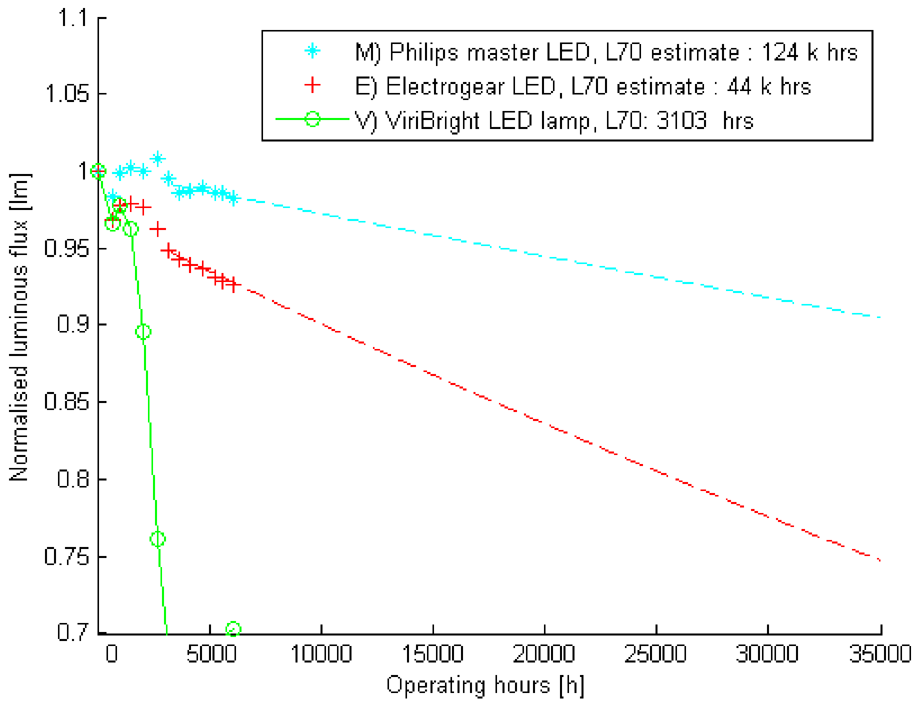

Figure 29: Extrapolated lumen depreciation of group 3.

The extrapolation suggests that the L70-value for surviving lamps would exceed 30000 hours. As discussed in methods, the TM-21-11 could only project and estimate performance 5.5 times the actual measurement duration. In this case, 33000 hours. Based on the data it is thus safe to estimate most of the lamps would have L70-value of 33000 hours but not more. This is, however, already an admirable result. Apart from complete failures and taking into account the bathtub curve presented in failure modes (chapter 3), the extrapolation suggests the modern LED lamps have practical lifetimes exceeding those of the CFL by several times. This has rather important implications for the next chapter, the cost estimation.

6.4 Operating cost estimation

Taking the extrapolated L70-values at face value, it is safe to assume an LED lamp could operate well into 30000 hours, three times longer than typical CFL. In order to compare different lamp technologies from consumer viewpoint, this thesis conducted a cost estimation for the purchase and operation of LED lamps versus CFL. Two different calculations were performed, one for 10000 hours (typical lifetime of a good CFL) and 30000 hours (estimated LED lifetime). It has to be also noted that the lifetime of CFL is strongly related to the amount of on/off cycles and thus the application of the lamp tremendously impacts the usability and lifetime of the lamp.

The cost estimation conducted by this thesis made some simplifying assumptions for multitude of reasons. First of all, the calculation assumes all the replacements are purchased at the beginning. This is reasonable, since the same model of LED or CFL probably wouldn't be on the market at the time replacement is needed. The price of electricity is assumed 17,45 cents/kWh, based on a 2012 figures for apartment buildings in Finland by Ministry of Employment and Economy [76]. No annuity or projection to present day value is performed. This was mainly because it is difficult to estimate how many hours a lamp is actually used daily or yearly. Finally, Tables 13 and 14 present operating cost estimates for 10 and 30 thousand hours.

Table 13: Operating cost of 10000 hours per lamp model.

Lamp model	Series code	Type	Estimated life [h]	Power consumption [W]	Cost of electricity [€]	Lamp purchase price [€]	Lamps needed (10000h)	Cost of lamps [€]	Total cost [€]
Airam MiniLED	**A**	LED	37747	9,8	17,07	24,95	1	24,95	**42,02**
Biltema LED lamp	**B**	LED	61835	11,7	20,35	18,90	1	18,9	**39,25**
Osram LED star	**O**	LED	37695	11,5	20,00	29,50	1	29,5	**49,50**
Philips LED lightbulb	**P**	LED	30957	9,8	17,10	26,95	1	26,95	**44,05**
Airam Mini H	**H**	LED	53305	10,4	18,22	27,95	1	27,95	**46,17**
V-light LED lamp	**C**	LED	32107	11,1	19,37	21,50	1	21,5	**40,87**
Osram LED superstar	**Q**	LED	5804	12,3	21,46	48,90	2	97,8	**119,26**
Verbatim LED lamp	**V**	LED	101040	10,0	17,38	29,50	1	29,5	**46,88**
Philips Master LED	**M**	LED	124060	10,8	18,85	38,71	1	38,71	**57,56**
ElectroGear LED	**E**	LED	43780	9,4	16,47	15,90	1	15,9	**32,37**
Viribright LED lamp	**D**	LED	3103	9,6	16,75	17,90	4	71,6	**88,35**
Airan Oiva 14W	**J**	CFL	8000	13,9	24,31	4,5	2	9	**33,31**
Airam longlife 15W	**I**	CFL	10000	15,3	26,70	9,99	1	9,99	**36,69**
Airam spiraali 14W	**K**	CFL	10000	15,4	26,87	8,99	1	8,99	**35,86**
Osram Dulux 14W	**L**	CFL	10000	13,5	23,61	9,95	1	9,95	**33,56**
Philips 60W clear	**-**	Inc.	1000	60,0	104,70	0,5	10	5	**109,70**

Table 14: Operating cost of 30000 hours per lamp model.

Lamp model	Series code	Type	Estimated life [h]	Power consumption [W]	Cost of electricity [€]	Lamp purchase price [€]	Lamps needed (30000h)	Cost of lamps [€]	Total cost [€]
Airam MiniLED	**A**	LED	37747	9,8	51,20	24,95	1	24,95	**76,15**
Biltema LED lamp	**B**	LED	61835	11,7	61,04	18,90	1	18,9	**79,94**
Osram LED star	**O**	LED	37695	11,5	59,99	29,50	1	29,5	**89,49**
Philips LED lightbulb	**P**	LED	30957	9,8	51,30	26,95	1	26,95	**78,25**
Airam Mini H	**H**	LED	53305	10,4	54,65	27,95	1	27,95	**82,60**
V-light LED lamp	**C**	LED	32107	11,1	58,11	21,50	1	21,5	**79,61**
Osram LED superstar	**Q**	LED	5804	12,3	64,39	48,90	6	293,4	**357,79**
Verbatim LED lamp	**V**	LED	101040	10,0	52,14	29,50	1	29,5	**81,64**
Philips Master LED	**M**	LED	124060	10,8	56,54	38,71	1	38,71	**95,25**
ElectroGear LED	**E**	LED	43780	9,4	49,42	15,90	1	15,9	**65,32**
Viribright LED lamp	**D**	LED	3103	9,6	50,26	17,90	10	179	**229,26**
Airan Oiva 14W	**J**	CFL	8000	13,9	72,92	4,5	4	18	**90,92**
Airam longlife 15W	**I**	CFL	10000	15,3	80,10	9,99	3	29,97	**110,07**
Airam spiraali 14W	**K**	CFL	10000	15,4	80,62	8,99	3	26,97	**107,59**
Osram Dulux 14W	**L**	CFL	10000	13,5	70,83	9,95	3	29,85	**100,68**
Philips 60W clear	**-**	Inc.	1000	60,0	314,10	0,5	30	15	**329,10**

Visibly, the CFL still rivals LED at 10000 hours due to its much lower purchase price. However, at 30000 hours this is offset by the need to replace the CFLs several times while the same LED lamp is (in most cases) still used. As time goes by, the higher energy consumption of the CFL also starts to build up costs where the LED can still manage with less electricity. It could be roughly stated that the LED becomes cheaper alternative to CFL if the LED lasts twice as long as the CFL. This result is also backed up by results from PremiumLight of EU [62].

Notably, during the testing period, the prices of LED lamps also decreased and manufacturers introduced new models to the market. Whilst at the time of purchase the cheapest available LED lamp was the 15.90 €ElectroGear, 60W equivalent LED retrofits were introduced in 2014 with retail prices less than 10 €. Although this thesis couldn't evaluate long-time performance of these lamps further, it shows the development trend in LED prices, which begin to rival the CFL. In this regard, the LED is also eating away the markets of CFL and in a few years the CFL probably fades into obscurity as the incandescent lamp did before it [2].

6.5 Goniometric measurements - luminous intensity distribution

As discussed in chapter 2.1.4 the luminous intensity distribution has an implication on the suitability of a non-standard lamp for a specific application. In the past, many luminaires were designed for the omni-directional incandescent lamp, which suggests possible problems with lamp with non-standard distribution of light. A predecessor studied angular distribution of CFL and LED lamps in 2010 and simulated illuminations with different luminaires [4]. A conclusion was that LED lamps of the time were most suitable for directional applications such as table-lamp.

This thesis thus measured all of the tested lamps in a goniometer. Polar graphs present the measured data, where the lamp socked faces upwards. The red and blue curves denote C planes of 0 and 90 respectively. While all of the lamp models were measured, only a few are presented here. Most of the LED lamps, for instance, had a hemisphere dome and similar distribution of light. The thesis thus focuses on differences and potential implications between lamp models. The analysis starts from the frosted-dome incandescent lamp, presented in figure 30. Some high-end retrofit lamps aim to mimic the incandescent lamp in this regard. Notable examples include domed CFL (Series I, L) and Philips Master LED (series M), presented in figures 31a and 31b.

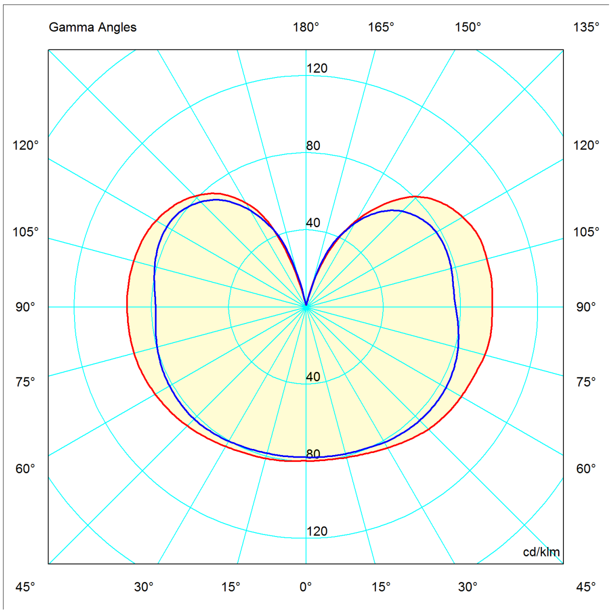

Figure 30: Luminous intensity distribution of generic 60W diffused incandescent lamp.

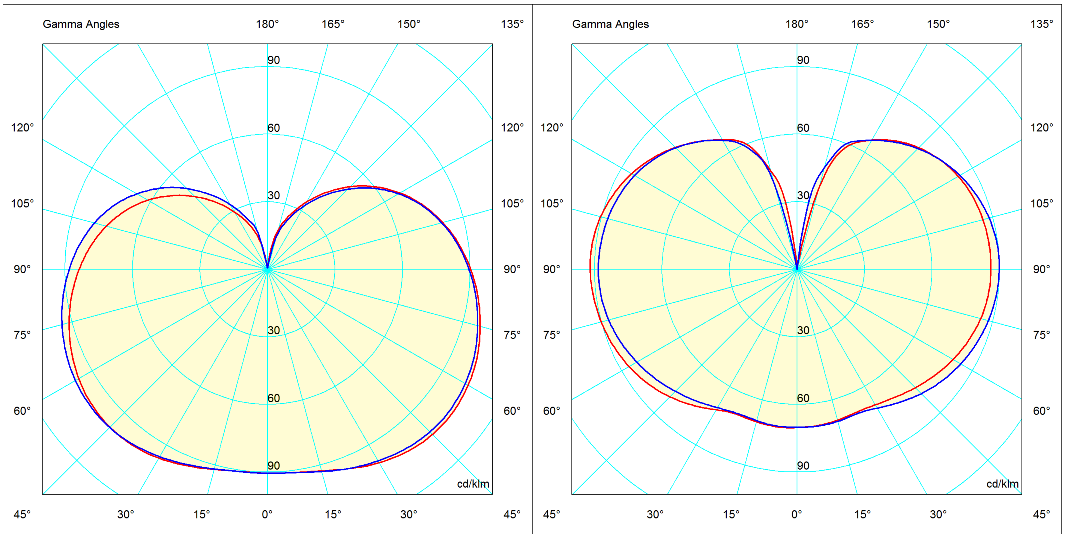

Figure 31: Luminous intensity distribution of a) Osram Dulux Domed CFL (L-series) b) Philips Master LED (M-series).

As can be seen from the figures above, the distribution is almost uniform except for the narrow band close to the socket. The incandescent lamp and Master LED provide light into the direction of the socket as well. In the CFL example, this light is blocked by the relatively large ballast driver at the lamp socket. Considering the distribution, a typical incandescent lamp would make a perfect solution for pendants and other applications requiring wide, uniform distribution of light. However, in more directional applications, such as table lamps and recessed ceiling luminaires, a reflector is needed to re-direct light. Reflectors cause losses and complicate the design of the luminaire and thus in these applications, a more directional lamp would be beneficial. Moreover, the visual effect must also be considered. Many floor-lamps, for instance, require light output from both directions along the axis of the lamp as well as sides, where the lamp-shade is. However, as the lamp-shade absorbs light, not too much is wanted on the mid-sector, perpendicular to lamps axis.

When the CFL was first introduced, it appeared in two basic variants, tubular and helical. The tubular lamp used to be overwhelmingly more common due to much simpler manufacturing process. The distribution of light, however, is distinctly different from incandescent lamp, as can be seen from figure 32a. The tubular CFL emits light perpendicularly to the axis of the lamp, but very little light up and downwards. The Biltema LED lamp (series B) exhibits similar behaviour, as the LEDs are arranged along the lamp axis in three lobes, somewhat analogously to Philips Master LED. A side-emitting lamp would require reflector in most applications and thus would be the most inefficient solution. For decorative floor-lamps, this type of lamp is the worst solution as most of the light is absorbed by the reflector with little to no light up- and downwards.

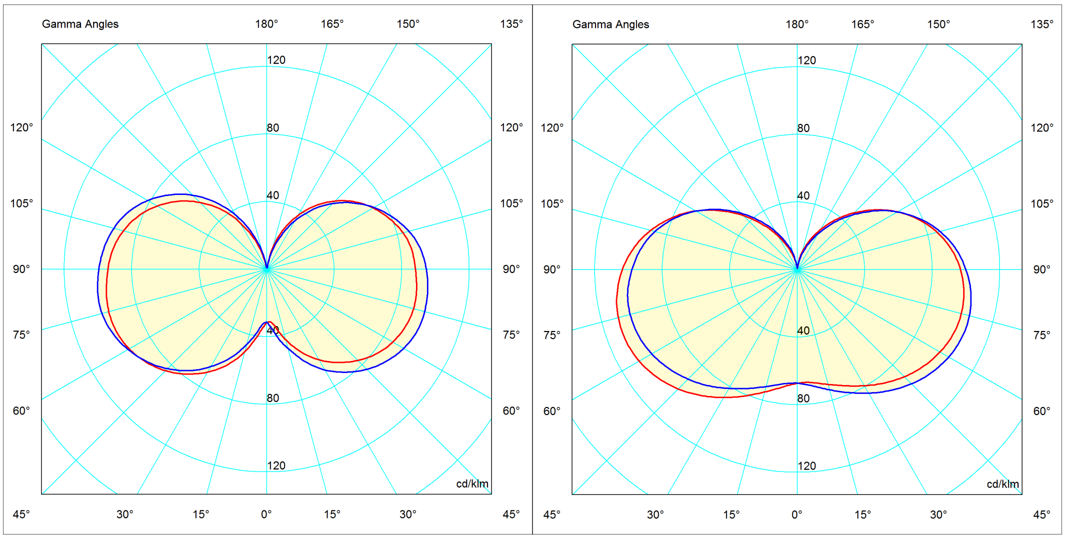

Figure 32: Luminous intensity distribution of a) Tubular CFL (J-series) b) Biltema LED lamp (B-series).

Most of the LED lamps, however, incorporate a hemisphere dome and planar LED module inside. This geometry more or less dictates that the luminous intensity distribution is quite directional. Most of the hemisphere-domed lamps exhibited similar distribution, displayed by figure 33a. Figure 33b presents series Q, which had a relatively flat dome, making it even more directional.

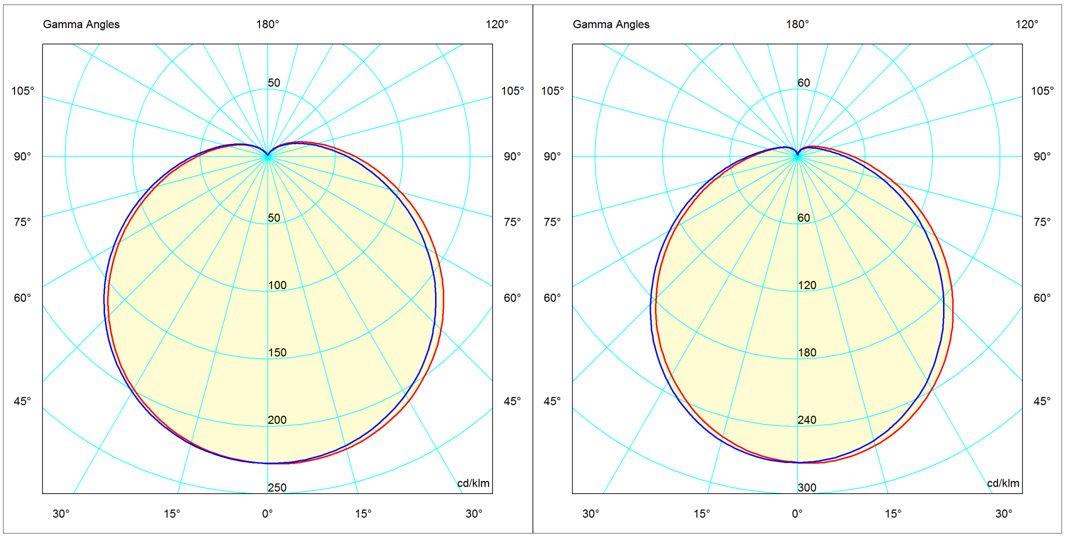

Figure 33: Luminous intensity distribution of a) Osram LED star (O-series) b) Osram LED superstar (Q-series).

Series Q is actually, by definition, directional as less than half intensity reaches 120° cone [11]. Directed lamps such as the hemisphere-domed LED lamps are most suitable for table lamps, recessed ceiling luminaires and downlights and practically all other applications requiring the use of reflectors to direct the light. As the lamp already directs light, losses in reflectors are minimised if not eliminated altogether.

The issue with different distributions of light between lamp models isn't so much their applications, but the information available to the consumer. All of the tested lamps were marketed and sold as non-.directional general purpose lamps. However, distribution of light does not emerge from package markings nor is it reported in any way. As demonstrated by the figures in this chapter and the application tests conducted by predecessor, differing distribution of light affects energy efficiency and visual effect as well [4]. Selecting a non-suitable lamp not only increases energy consumption, but may lead to negative user experience and thus a bad reputation for a technology as a whole. It is a conclusion of this thesis that the consumer should be informed about the distribution of light, as also noted in Energy Star package marking requirements and US DOE report [25] [65].

7 Conclusion

Very early into the market survey of chapter 4.3, the thesis discovered an enormous variety of LED lamps on the market. Whilst inferior, second-rate lamps were available only few years ago, most of the lamps sold domestically in the first half of 2013 were all of high quality. No longer were these lamps dim, bluish and prone to early failures, but capable and efficient retrofit lamps. It would appear the emergence of standards and stricter requirements has driven the development as intended by legislators.

Studies reviewed indicated a clear upward trend in LED lamp performance in recent years. Not only had the lamps reached the performance of CFL but also surpassed it by fair mark. It also became clear that American markets lead the development of LED retrofits and Europe somewhat lags behind. The literature review also discovered scarcity of LED performance data related to ageing. Only a number of ageing test reports were discovered and the raw lumen depreciation data isn't readily available. Thus, selecting analysis method for this thesis proved somewhat a challenge. Fortunately, non too many methods were available either, which limited the amount of review work needed. Ultimately the IES TM-21-11 was selected for extrapolation of the lumen depreciation data and analysis.

The lamps that were selected for the tests performed generally well. Luminous efficacy of the LED lamps surpassed contemporary reference CFL models by fair margin. Whilst LED lamps are still more expensive than comparable CFL, the prices are declining and LEDs make up the difference by other good qualities. All of the tested LED lamps lit up immediately to full brightness. The CCTs and colours of the lamps were pleasant and met regulations with only some exceptions. Finally, most of the lamps were truthful to the package labels and user information available.

During the ageing tests, the author screwed in and out an excess of 3500 lightbulbs during the testing period of 8 months, developing some professional skills in the process. The ageing test was divided into two parts, both revolving around constant-on stress test at 30 °C. The lumen depreciation and colour coordinates were measured at 500-hour intervals up to 6000 hours total. During the test period, all lamp failures were also recorded and analysed. Relatively few lamps failed completely, mostly due to driver failures. Lumen depreciation remained relatively low for most of the lamps, less than 5% in most cases. Two lamp models failed due to reaching L70-value (70% of initial luminous flux) during the testing period. The result also suggested the purchase price has little correlation with the lifetime of these lamps, putting more emphasis on a proper, sound design.

The ageing test results were extrapolated using TM-21 methodology. The findings suggests the L70-values for most of the lamps resides beyond 30000 hours. This implies that LED lamps would be cheaper than CFLs to use if they indeed reach this milestone. For periods less than 10000 hours, the CFL is still cheaper due to lower purchase price. However, LED lamps can reach efficacies exceeding 100 lm/W, twice as good as the CFL, and the prices of LEDs are plummeting. Soon the CFL will also have to surrender to the inevitable faith of the incandescent lamp. This thesis also recommends a follow-up study on the tested lamps to validate the TM-21 prediction.

This thesis also came upon an issue that remains yet unsolved. As the LED lamps come in many shapes and sizes, so does their luminous intensity distribution differ from one another and the reference incandescent lamp. Different distributions are suitable for different applications, implying great energy saving potential. However, the distribution of light is not obvious from package labels in the EU. This crucial shortcoming is preventing consumers from selecting a correct lamp for an application, maybe even creating negative reputation for the LED technology. In USA, Energy Star requires the use of special application icons if the distribution of light differs from standard incandescent lamp reference. This thesis recommends the adoption of functionally similar icons in European package labels as well to avoid confusion and negative user experience as well as to further potential energy savings. It remains to be seen if such an important shortcoming will be addressed in the future by legislative bodies inside the EU.

It could also be argued that instead of LED retrofit lamps, the industry should focus on more efficient luminaires. Whilst it is true that the Edison screw socket limits the design flexibility and possibly the efficacy, it also provides a standardised hardpoint, around which so many luminaires have been designed. Given the worldwide popularity of the screw socket, it seems unlikely E27 retrofit lamps would disappear from the market in foreseeable future. Thus, when the last E27 LED retrofit breathes it's last, the lighting industry has probably been transformed beyond recognition by LED technology. It is impossible to predict what kind of new solutions coming years will witness. It took the incandescent lamp roughly 50 years on the market to develop into the familiar tungsten filament lamp we all came to know and love. Progress with LEDs has been even faster and it will revolutionise the industry even more than emergence of electric lighting did 150 years ago.

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